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A new methodology to identify and quantify material resource at a large scale for earth construction – application to cob in Brittany

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Abstract

A new methodology based on the cross-referencing of spatialized pedological and heritage data is proposed to identify and quantify soil resources available for earth construction. The paper underlines the pedological particularities of areas containing earth heritage and uses these particularities to propose criteria to assess the suitability of soils for modern earth construction. The methodology applied at the regional scale in France (for a given area of 27,200 km^2 in Brittany) enabled to specify five new texture classes (balance between clay, silt, sand and gravel content) of suitability for cob soils. This result calls into question recommendations available in the literature.

The methodology also provides data on the scale of availability of the resource to repair earth built heritage (cob) or to build new low impact buildings with integrated modern cob walls. In the studied area the potential waste recovery of 2.8 Mt per year is measured, highlighting the large availability of materials for earth construction. At least 23 % of earthwork wastes of Brittany are suitable for earth construction (0.7 Mt). However, earth remains a non-renewable material and this resource has to be properly managed, requiring an appropriate building design and maintenance in order to increase longevity and to avoid the use of admixture, preventing earth reversibility at end of life.

Highlights

- Proposed methodology is based on cross-referencing of spatialized pedological and heritage data

- The earthwork waste reuse capacity for earth construction is estimated at regional scale
- The first map of earth construction material availability at regional scale is proposed
- Five texture classes of suitability for cob soils are defined for Brittany
- Texture results call into question recommendations available in the literature

Keywords: cob; earthwork waste; earth construction; rammed earth; adobe; pedology

1 Introduction

The construction sector consumes a large volume of natural resources and is responsible for about 50 % of wastes production in the European Union [1–5]. These wastes have a negative environmental impact [2–4] and it is increasingly difficult to find suitable landfill areas [4,5]. Among these construction wastes, about 75 % are soils and stones [1,6]. Earth construction is a possible market for earthwork wastes, but no data is available about the quantification of local stocks and flows of soils suitable for earth construction. Therefore, the resources to get a low impact building must be found locally, a mission that is challenged by the local soil variability [7]. Overall, this situation prevents modern earth building markets to develop.

The aim of this paper is to propose a novel methodology to identify and quantify soil resources available for earth construction in order to assess the potential market share of the earth construction sector and waste reduction by the construction industry.

Suitability of earth for construction purposes is usually determined using a geotechnical approach, aimed at enhancing the mechanical strength of earthen specimens carried out in the laboratory [8–10]. The most cited criterion to assess earth suitability is texture, i.e. balance between clay, silt, sand and gravel content [11]. Consequently, grading envelopes adjusted to each earth construction technique were proposed in the literature [8,12–17]. However, textures of materials collected in vernacular earth heritage buildings do not fit inside those grading envelopes [18–23]. Thus, grading envelopes available in the literature failed to give full account of the diversity of earth employed for construction [24].

Another approach to identify material suitability for construction is to analyse materials traditionally used in heritage buildings [18–21]. Soils for vernacular earth construction were excavated directly on-site or at a distance less than 1 km away from the construction site [19,21,24–29]. As a consequence, the presence of earth heritage highlights the presence of soils suitable for construction [19,21]. A high proportion of earth building heritage indicates a priori (1) a large availability of earth, (2) a good quality of earth allowing easy implementation, (3) a high longevity of cob buildings and (4) a favourable cultural context. Vernacular soil selection is the result of time-tested empirical experimentations and the proposed methodology aimed at rediscovering this past know-how and to consider it for modern earth building.

Several authors identified material sources through comparison between materials inside walls of heritage buildings and available local materials using geological analysis [18–20,22,27] and, more rarely, pedological analysis [19,21]. Geological maps are preferred to pedological maps for material source identification as they provide more detailed and homogeneous cartographic information [21]. However, pedology is considered as more relevant than geology for identification of earth material sources [13,19,21]. Recently, in France, the completion of regional pedological maps offers new opportunities to analyse soils next to earth heritage. Hence, the new methodology proposed in this paper is based on the cross-referencing of spatialized pedological and heritage data. Pedological particularities of areas containing earth heritage are highlighted and these particularities are used to propose criteria to assess the suitability of soils for vernacular earth construction and scale of availability of the resource to repair earth built heritage or to build new low impact buildings with integrated modern earth walls. This new methodology is exemplified in this paper in Brittany (France) but can be extended to regions having heritage and soil information. For this study, Soils of Brittany [30] and the Cultural Heritage of Brittany databases [31] were used.

In Brittany the vernacular earth construction technique is cob. The cob technique employs earth elements in a plastic state, implemented wet and stacked to build a monolithic and load-bearing or freestanding wall [24]. The paper deals with cob, but the use of the methodology can be expanded to other earth construction techniques, like rammed earth or adobe masonry for example.

2 Methodology description

2.1 Soil suitability determination

The relative densities of earth buildings are an indicator of suitability of soils for earth construction [21]. Relative densities were calculated by cross-referencing between heritage and soil databases covering the same geographical area. The spatialized heritage database must provide homogeneous information on the vernacular architecture of the studied area and must concern all vernacular materials (timber, stone, earth, solid bricks). The described methodology is designed for the French soil cartographic representation called "*Référentiel Régional Pédologique*" (RRP), but can be adapted to other cartographic representations.

Soil cartographic representation by the RRP is a set of polygons, spatially delineated, defining Soil Map Units (SMUs) [32]. Since soils show rapid variations in three dimensions, each SMU corresponds to a soil landscape, i.e. a collection of soils, defined as a Soil Type Unit (STU), developed in a common environment. Each SMU includes 1 to 10 STUs which are not spatially delineated [30,33] (Figure 1). Each STU is divided into strata, representing the vertical variability of soil. Pedological characteristics of SMUs, STUs and strata (such as depth and thickness, texture and Cation Exchange Capacity) are gathered in a semantical database (Figure 1).

The aim of the calculation is to identify the pedological characteristics (clay, silt, sand, gravel content and Cation Exchange Capacity) of soils according to their suitability with earth building. This calculation is carried out in 3 steps: (1) calculation of the frequency of earth heritage building for each Soil Type Unit, (2) exclusion of Soil Type Unit which can be regarded as outlier values, (3) calculation of minimum and maximum values of pedological characteristics of the Soil Type Units of a same frequency class. The calculation is detailed below and parameters are detailed in Table 1.

Heritage and pedological data are combined in a Geographic Information System so that the total heritage and earth heritage number of buildings, respectively *TOT_SMU* and *EARTH_SMU*, can be determined for each SMU. The total and earth heritage building numbers of a SMU are attributed to the STUs that compose the SMU with respect to the surface proportion of STUs in the SMU ($SURF\_STU_{SMUi}$). The total numbers of heritage and earth heritage buildings of a STU, respectively *TOT_STU* and *EARTH_STU*, are the sum of total or earth heritage buildings of the STU on the SMUs inside which it is present (Figure 1):

$$TOT\_STU = \sum_i SURF\_STU_{SMU_i} \times TOT\_SMU_i \quad (1)$$

$$EARTH\_STU = \sum_i SURF\_STU_{SMU_i} \times EARTH\_SMU_i \quad (2)$$

In order to discuss the relative densities of vernacular earth buildings of the studied area, the frequency of earth buildings ($FREQ_{STU}$) are calculated for each STU:

$$FREQ_{STU} = \frac{EARTH\_STU}{TOT\_STU} \quad (3)$$

This calculation is exemplified using a theoretical case in Figure 2.

Earth frequencies of STUs go from 0 to 1 and are divided into 11 frequency classes (Table 2). The frequency describes the suitability of STUs with regard to earth construction: the higher the frequency, the higher the suitability. Absence of earth heritage can reflect a poor suitability of available soils but this can also be explained by historical or social reasons. Consequently, suitability of soils is assessed using frequency classes greater than 1%, but it is not possible to state that characteristics of strata with frequencies lower than 1% are not compatible with earth construction. The frequency of a stratum ($FREQ_{STRATA}$) is assumed to be equal to the frequency of its STU ($FREQ_{STU}$).

The standard deviation σ_FREQ_{STU} of $FREQ_{STU}$ is calculated as below:

$$\sigma\_FREQ_{STU} = \sqrt{\frac{FREQ_{STU} \times (1 - FREQ_{STU})}{TOT\_STU}} \quad (4)$$

A maximum standard deviation $\sigma\_FREQ_{STU\_MAX}$ is set by the researcher, in order to exclude outlier values.

In order to ensure that the data is representative, a minimum total heritage building per STU, n_{STU}, is calculated for a 95% confidence interval, a margin of error e and for total heritage buildings of the STU N:

$$n_{STU} = \frac{1.96^2 \times N}{1.96^2 + (2e)^2 \times (N-1)} \quad (5)$$

Consequently, only STUs having a standard deviation σ_FREQ_{STU} lower than $\sigma\_FREQ_{STU\_MAX}$ and counting more than n_{STU} total heritage buildings are taken into consideration in the analysis.

Topsoil is rich in organic matter and was therefore inappropriate for construction purpose. Since soil excavation was traditionally made by hand, only subsoil near the surface was used, i.e. a large surface area and a thin layer of soil below the topsoil [24]. This is why organo-mineral (A, LA, H) and deep (appearance depth > 50 cm) strata were not considered in the analysis.

Pedological characteristics (*CHARACTER*) were determined during the soil of Brittany campaign [30,33]. The available pedological characteristics of the database are clay, silt, sand, gravel content and Cation Exchange Capacity (CEC). During the soil of Brittany campaign [30,33] particle size distribution was determined by wet sieving for fractions greater than 50 µm and by Robinson pipette method for smaller fractions, according to

French Standard NF X 31-107 [34]. CEC of the database was determined using the Metson test method [35], according to French Standard NF X 31-130 [36].

The pedological database contains modal, and, when available, minimum and maximum value for each characteristic of strata. Minimum (*MIN*) and maximum (*MAX*) values illustrate the range of value that can vary spatially due to natural variations of soils, each strata resulting from various discrete observations. When minimum and maximum values were available, these variations were taken into account by calculation of an estimated confidence interval. As the average and standard deviation are unknown, a half-confidence interval ($CONF\_INT_{STRATA}$) was estimated as the third of the range of the values:

$$CONF\_INT_{STRATA} = \frac{MAX - MIN}{3} \tag{6}$$

Consequently, the confidence level of the estimated confidence interval is not determined.

For each frequency class i ($CLASS_i$), the average value of each characteristic ($CHARACTER_{STRATAj}\_CLASS_i$), weighted by the earth frequency of the j[th] strata ($FREQ_{STRATAj}$) is calculated:

$$\overline{CHARACTER_{STRATA_j}\_CLASS_i} = \frac{\sum_{i,j} CHARACTER_{STRATA_j}\_CLASS_j \times FREQ_{STRATA_j}}{\sum_i FREQ_{STRATA_j}} \tag{7}$$

For each frequency class i ($CLASS_i$), the average value of confidence interval of each characteristic ($CONF\_INT_{STRATAj}\_CLASS_i$), weighted by the earth frequency of the j[th] strata ($FREQ_{STRATAj}$) is calculated:

$$\overline{CONF\_INT_{STRATA_j}\_CLASS_i} = \frac{\sum_{i,j} CONF\_INT_{STRATA_j}\_CLASS_j \times FREQ_{STRATA_j}}{\sum_i FREQ_{STRATA_j}} \tag{8}$$

Finally, the minimum and maximum value of a characteristic, for a frequency class, respectively $MIN_{CHARACTER}\_CLASS_i$ and $MAX_{CHARACTER}\_CLASS_i$, are calculated:

$$MIN_{CHARACTER}\_CLASS_i = \overline{CHARACTER\_CLASS_i} - \overline{CONF\_INT\_CLASS_i} \tag{9}$$

$$MAX_{CHARACTER}\_CLASS_i = \overline{CHARACTER\_CLASS_i} + \overline{CONF\_INT\_CLASS_i} \tag{10}$$

2.2 Earth resource quantification

In order to reflect vernacular extraction conditions, soil suitability was determined considering the horizons with depth less than 50 cm only. Modern excavation means give access to deeper soils this is why the quantification calculation takes into account all pedological horizons, whatever their depths are. Clay, silt, sand, gravel content and CEC minimum and maximum values of each frequency class are used to identify strata suitable for earth construction in the pedological database. The volume of earth suitable for construction for each frequency class (VOL_EARTH_{CLASSi}) is the sum of the volume of strata suitable for construction:

$$VOL\_EARTH_{CLASS_i} = \sum THICK_{STRATA} \times SURF\_STU_{SMU} \qquad (11)$$

The volume of earth is calculated considering several frequency classes. The classes to be considered for this calculation are set on expertise:

$$VOL\_EARTH \ = \ \sum_i VOL\_EARTH_{CLASS_i} \qquad (12)$$

And the proportion of soils suitable for earth construction (*PROP_SOIL*) on the studied area is:

$$PROP\_SOIL \ = \frac{VOL\_EARTH}{VOL\_SOIL} \qquad (13)$$

Where *VOL_SOIL* is the volume of all soils of the studied area.

To provide a cartographic representation of the resource availability, the volume of soils suitable for construction (VOL_EARTH_{SMUi}) is calculated for each SMU:

$$VOL\_EARTH_{SMU_i} = \frac{\sum VOL\_EARTH\_STU_{SMU_i}}{n\_STU_{SMU_i}} \qquad (14)$$

With $VOL\_EARTH\_STU_{SMUi}$ calculated according to equation (11) and n_STU_{SMUi} the number of STU in the considered SMU.

Resource availability is also presented by surface. The surface of a SMU suitable for earth construction ($SURF\_EARTH_{SMUi}$) is the sum of the surface of the STUs of this SMU suitable for earth construction ($SURF\_EARTH\_STU_{SMUi}$):

$$SURF\_EARTH_{SMU_i} = \ \sum SURF\_EARTH\_STU_{SMU_i} \qquad (15)$$

3 Application to cob in Brittany (France)

3.1 Study area

Brittany is part of the Armorican Massif. This Massif is the result of, at least, three orogenies. Rocks of this geological domain are mostly old sedimentary rocks, more or less metamorphosed (sandstone, schist), metamorphic rocks (gneiss), magmatic rocks (granite, rhyolite) and loess deposits [37–39]. Paedogenesis of the massif is dominated by darkening and leaching. Locally, podsolization and a paleopedogenesis, marked by a fersiallitization, are mentioned [40].

Among Armorican rocks, Brioverian schists are sensitive to alteration and thus produced thick soils that favoured cob construction [18,41–44]. Soils deriving from other local parental materials (granite, sandstones, Cambrian schists) were also employed for cob construction [18]. Nevertheless, the correlation between geology and cob heritage distribution in Brittany did not provide satisfactory results [43].

3.2 Heritage and pedological databases

Since 1964, historians and architects of the *Service du Patrimoine Culturel* of Brittany have carried out a systematic field inventory of regional cultural heritage and maintained a regional database [31]. This heritage database was homogenized in order to create a unique point database, counting 113,824 entities (buildings, castle mound, archaeological sites, crosses, statues …). To focus on vernacular building heritage, the items without information on building materials, built after 1925, of military or religious character, or built with a modern material (steel, glass, concrete, hollow brick) were removed from the database. Subsequently, a database of 48,230 heritage buildings was obtained. Among these 48,230 buildings, 7,133 were identified as cob buildings, which represents 14.8% of the studied heritage (Figure 3) and 24% of the estimated total cob heritage of Brittany [44]. These buildings date back as far as the 16th century (Figure 4). Other heritage building materials were stone, timber and solid brick.

The heritage survey of Brittany is not yet complete. Municipalities having no data were therefore not considered in this study. The study area represents 54% of the total surface of Brittany and the proportion of study area inside and outside the vernacular cob area, determined using literature data [41,43,45,46], is well balanced (Figure 3). The geographical distribution of the study area reflects the heritage distribution of Brittany and is therefore considered as satisfactory.

Soil information at 1:250,000 map scale in Brittany was obtained in the framework of the "*Référentiel Régional Pédologique"* (RRP) project, started in 2005, certified in 2012 and available online [30].

3.3 Data processing

The minimum total heritage building per STU, n_{STU}, is calculated according to equation (5), considering $N = 48230$ and $e = 0.1$: $n_{STU} = 96$. The $\sigma\_FREQ_{STU\_MAX}$ is set to 0.03. Among 288 STUs, 68 STUs verify those two parameters and are considered for the analysis. Five of these STUs had missing information and were therefore not considered for the analysis. Cob frequency ($FREQ_{STU}$), frequency class (*CLASS*) and standard deviation (σ_FREQ_{STU}) of the 63 STUs employed for the analysis are presented in Table 3. Frequencies range from 0.00 to 0.49. As a consequence, 6 frequency classes were considered (Table 3).

4 Results and discussion

4.1 Resource identification

4.1.1 Texture

Textures (clay, silt, sand and gravel contents) of pedological strata for 5 frequency classes are presented in Table 4, and the 20-50% cob frequency textures are presented in Figure 5. The coloured surfaces of the radar graphical representation of Figure 5 allow an easy comparison between recommended textures, but only the extremum clay, silt, sand and gravel contents are to be considered. They do not present any minimum gravel content, only a maximum value, ranging from 2% for 40-50% frequency class to 30% for the 1-10% frequency class (Table 4), indicating that vernacular cob earth in Brittany had no or low gravel content.

Gravels are sometimes observed in vernacular cob walls. These gravels might have been added on purpose but most of the time it might have been already present in the excavated soil. As highlighted by [24] gravels can play the role of shrinkage crack barrier and therefore temper the drying shrinkage effect. However, most of the time, natural fibres were added in order to play this role [24]. Past builders prepared the cob mixture by trampling the material bare foot of wearing wooden clog. Large gravels have made the cob mixing difficult. Moreover, cob walls were often cut to rectify their surface and gravels disturbed this action [24,47]. This is why, most of the time, large gravels were removed from earth. Consequently, past builders developed specific cob techniques adapted to earth with high gravel content, but, when possible, little or zero gravel content earth were preferred. From our field observations in Brittany cob heritage walls with large gravels are an exception. Results are consistent with the constraints of the vernacular cob process.

Clay, silt and sand content of strata having an affinity with cob have a minimum and a maximum value (Figure 5, Table 4). These three granular fractions were therefore required for cob construction. The balance between these three fractions is clearly in favour of silts, since they represent 37% to 57% of the material (Figure 5, Table 4). Among the large variety of soils available in Brittany, cob heritage preferentially set up on silty soils (Figure 5).

Fine earth fraction (< 2 mm) represents the clay, silt and sand content of earth without coarse elements (Clay + Silt + Sand = 100%). The texture of fine earth are depicted by points in the GEPPA texture triangle [48], conventionally used for French soil identification (Figure 6). In this representation, whatever the gravel content, sum of clay, silt and sand content is 100%.

Among soils of Brittany, textures of fine earth with a 1-50% cob frequency are the siltiest (Figure 6). The texture of fine earth of 40-50% cob frequency is mostly silty, and with lower cob frequencies, the silt fraction decreases in favour of the sand fraction and maximum clay content slightly increases (Figure 6, Table 5).

4.1.2 Comparison of texture results with existing recommendations

Different grading envelopes are proposed in the literature [13–15,17]. These recommendations were adapted and are presented in Figure 7 and Figure 8(a).

The comparison between texture of strata, identified as having an affinity with cob heritage in Brittany, with recommended textures for cob available in the literature (Figure 7) indicates that: (1) clay content of cob with a 20-50% cob frequency is inside the literature recommendations [13–15,17]; (2) recommendations from the literature propose a minimum gravel content [13–15,17], supporting the hypothesis that gravels are necessary in cob material, which contradicts the results of this study; (3) the balance between sand and silt is in favour of sand in the literature [13–15,17] and in favour of silt in this study.

As for texture of earth with coarse elements, the texture of fine earth within the cob area of Brittany widely differs from recommended texture of fine earth available in literature (Figure 8(a)). The same difference has been highlighted by several authors for vernacular cob materials [18–21], vernacular adobe [22] and vernacular rammed earth materials [23,29]. In fact, earth suitability recommendations are based on a theoretical laboratory approach, whereas vernacular soil selection is the result of time-tested empirical experimentations. Textures identified in this study enlarge the volume of possible earth material suitable for cob construction and call into question recommendations available in the literature.

4.1.3 Comparison of texture results with existing data

Data on textures of heritage cob buildings are available for Germany [47] and the United Kingdom [20]. These data have been adapted and are presented in Figure 8(b). Fine earth material of cob heritage in Germany, more precisely in Saxony, Saxony-Anhalt and Thuringia [47], have a sand/silt balance quite similar to high frequency fine earth texture determined for cob in Brittany, but their clay content (2-6%) is smaller (Figure 8(b)).

In Devon (United Kingdom), it is demonstrated that traditional cob walls built with soils derived from Permo-Triasic rocks had higher propensity to structural failure than those derived from the “Culm measure” rocks [20]. Textures of fine earth, from what the authors called a “high risk zone”, labelled by red circles on Figure 8(b), are outside the texture of fine earth identified for cob in this study. Results are therefore in accordance with those of Keefe et al. [20]. Nonetheless, even if considered as “high risk” materials, historical builders in Devon managed to build cob houses with these earth. Thus, textures of earth identified as suitable for traditional cob in Brittany do not cover the entire textures of earth employed in Devon’s vernacular cob. Since no information was provided on texture of earth of undamaged cob walls, it was not possible to state if earth suitable for cob in Devon are inside or outside the cob area defined in the present study (Figure 8(b)).

Hence, the results of this study are relevant only for Brittany. Nevertheless, silty textures of fine earth seem to have been preferred by past builders, at least in Brittany and Germany.

4.1.4 Cation Exchange Capacity and clay

Cation Exchange Capacity (CEC) of a soil is intimately linked to the specific surface area of clay and organic matter content [49–52]. CEC of strata with a 10-50% cob frequency range from 2.8 to 6.2 $cmol^{+}.kg^{-1}$ (Table 4), whereas CEC of all strata of Brittany range from 0.5 to 106.0 $cmol^{+}.kg^{-1}$. Strata with a 10-50% cob frequency (Figure 9(a)) of Brittany exhibit CEC which corresponds to no or little organic matter content and low activity clay soils [53].

The organo-mineral strata were not taken into account for the data analysis (section 2.1), thus organic matter content of strata considered in the analysis is very low, and its contribution to CEC is limited. Assuming that CEC can be attributed to clay only, the CEC of the clay fraction was calculated (CL_CEC, Table 4). According to their CEC, the clay fraction of strata with a cob affinity is mainly composed of Illite and Kaolinite clay types, i.e. clay with low or medium sensitivity to water (Table 4, Figure 9(b)). This is in agreement with the literature: cob mixture is implemented at plastic state and drying shrinkage could generate wide cracks that might affect mechanical resistance.

In earth with a 20-50% cob frequency, when CEC of clay (CL_CEC) increases, the clay content decreases (Figure 9(b)): the more the specific surface of the clay, the less the required clay content. A linear relationship is proposed between Clay content (CLAY) and Cation Exchange Capacity of Clay (CL_CEC) for cob in Brittany with a correlation coefficient of 0.78 and a standard error of 2.3. This relationship, together with its standard deviation, is presented in Figure 9(b), the upper standard error line is the value above which the specific surface developed by clays might generate harmful shrinkage, and the lower standard error line is the value below which the specific surface developed by clays might not be enough to provide sufficient cohesion to the material. There is an optimum clay content [24,54–56] and this optimum clay content decreases when CEC of clays increases (Figure 9(b)).

Past masons added elements to the cob mixture to play the role of shrinkage crack barriers, such as fibres, in order to employ earth that would have shrunk too much [24]. As the fibre content and the cob variation technique employed for heritage cob buildings studied here are unknown, this might have affected the correlation coefficient of the clay content and clay CEC relationship (Figure 9(b)).

4.1.5 Earth and cob process

There are many variations of the vernacular cob construction process resulting from the adaptation of the technique to local environments [24]. The earth could have been adapted to the cob process. For example the addition of fibres was often used to limit shrinkage cracks and made it possible the use of too clayey earth [13,24,57]. The process could have also been adapted to the earth. The rectification of the surface of cob walls containing large gravels could be done by beating the surface of the wall [24,26,44]. Thus, a strong link occurs between the available earth and the process employed. The frequencies calculated in this study are valid for vernacular techniques traditionally employed in Brittany, under this local climate and social context. The most widespread vernacular cob technique of Brittany consisted in treading earth and straw into a plastic consistency, stacking clods of cob into the wall, compacted by treading action and rectifying the faces of the walls by a trimming action (case (a), [24]). However, other cob techniques are encountered in Brittany. As no information is available about the technique employed for cob building construction in the heritage database, it is not possible to discuss the suitability of earth with any specific cob variation technique.

In the area of a given SMU, a high proportion of cob heritage indicates a favourable context. It is assumed that the highest frequency class depicts the most suitable soils of Brittany for vernacular cob construction. Because these results need to be compared to those of other vernacular cob regions, they should be used only as a decision support tool for modern cob applications and not for standardisation purposes.

4.2 Resource quantification

The cob resource quantification was carried out according to section 2.2, considering a 10-50% cob frequency class. This large frequency class is thought to better reflect the earth availability in a modern context for cob.

A geographical representation, by percentage of surface and by percentage of volume, calculated for each SMU, of soils suitable for cob in Brittany, is presented in Figure 10. Geographical distribution of cob heritage, drawn according to several literature sources [41,43,45,46] is also presented in Figure 10. Thanks to the percentage of available earth calculated, a quantitative estimation of the availability of the resource at regional scale is proposed in Table 6.

The availability of cob soils, expressed in surface, is greater in the East part of Brittany and well correlated with the geographical distribution of cob heritage, whereas there is no correlation between the geographical distribution of cob soils by volume and cob heritage (Figure 10). This result suggests that the geographical continuity of the resource is more important than the volume of the resource in order to allow the development of a local earth construction culture. Nowadays, modern excavation provides access to resources that were not accessible by manual excavation means. The representation of the resource by surface should be regarded as a representation of the availability of cob soil in a historical context, and the representation by volume should be regarded as a representation of the availability of cob soil in a modern context.

Macro scale orders of magnitude of the volume of available soil resource for cob were calculated (Table 6). The volume of soil available for vernacular cob technique in Brittany was estimated at 6.8 billion m^3, i.e. 8.8 billion tonnes, and represents 23% of total soils of Brittany. The estimated proportion of the regional cob resource already consumed by past builders is 0.03%. The hypothetical consumption of the entire resource would enable the construction of 88 million homes and if all housing of Brittany were made of cob, 2.1% of the cob resource would have been consumed (Table 6). These figures illustrate the huge availability of earth material. These calculations are based on 10-50% cob frequency soils and considering vernacular cob technique only.

Considering that it is possible to use other types of earth with mechanized cob, that skilled craftsmen are able to use earth outside the 10-50% cob frequency area and that other earth construction techniques could be employed, these orders of magnitude should therefore be regarded as minimum values in a modern earth construction context.

Nonetheless, soil is a non-renewable material on the human time scale and it provides various ecosystem services concerning provisioning, regulating, cultural and supporting services [58]. Extraction of earth for construction might impact multifunctional roles of soil. Management of the consumption of this resource should therefore be carefully considered.

Currently, earthworks excavations generate large amounts of landfilled soils. In Brittany, 2.8 million tons of soils are landfilled every year. Considering that 23% of these landfilled soils are suitable for cob, in 2012, 0.6 million tons of earth were available in Brittany and would have enabled the construction of 52% of individual housing of Brittany that year (Table 6). The resource of earth suitable for cob in Brittany is huge and earthwork extractions already provide large amounts of these earth every year. This high-quality construction material could be valued in the building sector, instead of ending up as waste in landfills.

5 Conclusion

A novel methodology, based on the cross-referencing of pedological and heritage data, was proposed to identify the pedological/geotechnical characteristics (clay, silt, sand, gravel content and Cation Exchange Capacity) of soils employed in vernacular earth buildings.

The methodology applied at the regional scale in France (for a given area of 27,200 km^2 in Brittany) enabled to specify five new texture and Cation Exchange Capacity classes of suitability for cob soils. Texture results of this first application call into question recommendations available in the literature and further investigations are needed to highlight the reasons for these differences.

Using those characteristics, the first map of availability of cob earth material at regional scale has been drawn and it was estimated that 23 % of earthworks wastes, in Brittany, could be upcycled for earth construction. This quantification is a minimum value, since other soils could be used with mechanized cob techniques or by skilled craftsmen and other earth construction techniques could be employed. The results highlight the large availability of materials for earth construction in Britany. However, earth remains a non-renewable material and this resource has to be properly managed, requiring an appropriate building design and maintenance in order to increase longevity and to avoid the use of admixture, preventing earth reversibility at end of life.

This novel methodology is very promising since it provides valuable data for economic and environmental assessment and significant results for the discussion on soil suitability to repair earth built heritage or to build new low impact buildings with integrated modern earth walls. To further the discussion on the identification and quantification of soils for construction, the same methodology should be applied to other regions with different earth construction techniques.

6 Acknowledgement

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Captions for figures

Figure 1. Pedological database: Soil Map Units (SMUs) are a spatialized depiction of soil landscapes at a scale of 1:125,000, SMUs are composed of a proportion, expressed in surface, of various Soil Type Units (STUs) and STU consist of several strata. Only SMUs are delineated.

Figure 2. Exemplification of earth frequency calculation for two hypothetical Soil Type Units among 3 Soil Map Units

Figure 3. Maps of available information in Brittany concerning Heritage database [31], and vernacular cob area of Brittany (a) [41,43,45,46]; 1:250,000 soil map figuring complex Soil Map Units (SMU) (b) [30]; map of municipalities possessing heritage data, defining the study area, together with vernacular cob area of Brittany (c) [41,43,45,46].

Figure 4. Temporal distribution of cob buildings of the studied area.

Figure 5. Texture of soils of 40-50 %; 30-40 % and 20-30 % cob frequency classes (a) and comparison of these textures (20-50 % cob frequency) with all soils of Brittany (b).

Figure 6. Texture of fine earth of strata of Brittany according to their cob frequency (a) (diamond are mode values and error bars are estimated confidence interval) and cob frequency classes (b).

Figure 7. Comparison between texture of soils with a 20-50 % cob frequency identified in Brittany and recommended texture available in literature, proposed by Morris [17] (a), Harries et al. [14] (b), Keefe [13] (c) and Jaquin and Augarde [15] (d).

Figure 8. Confrontation of texture of fine earth identified as suitable for vernacular cob construction in Brittany with cob recommended texture available in literature (a) [13–15,17] and texture of fine earth of German cob soils [47] and damaged cob walls built with soils derived from Permo-Triasic rocks in the United-Kingdom (b) [20].

Figure 9. Cation Exchange Capacity (CEC) of strata of Brittany plotted against cob frequency (a) and clay content of strata with a 20-50 % cob frequency plotted against the CEC of clay fraction (b).

Figure 10. Map of SMU resource availability for vernacular cob in Brittany, considering strata with a 10-50 % cob frequency by surface (a), by volume (b) and comparison with vernacular cob area [41,43,45,46].

Captions for tables

Table 1. Definition of parameters used for soil suitability determination

Table 2. Frequency classes of earth buildings within STU.

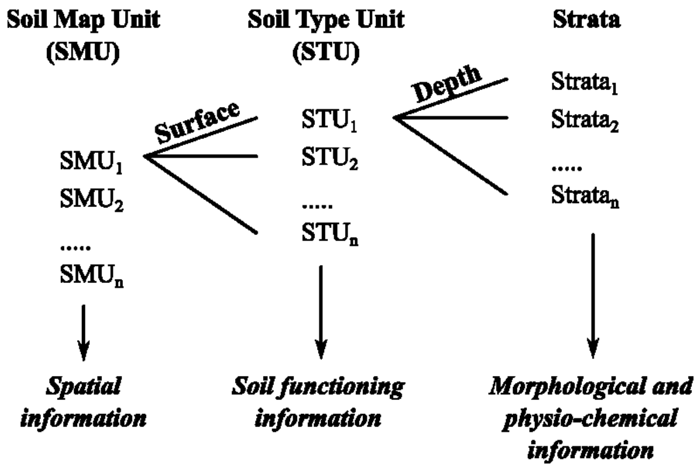
Table 3. Frequency, frequency class and standard deviation (σ_FREQSTU) of Soil Type Unit (STU), calculated according to section2.1. Description of STUs can be found online: http://www.sols-de-bretagne.fr/ [30].

Table 4. Texture (in percentage by mass), Cation Exchange Capacity (CEC) of soils and Cation Exchange Capacity of clay fraction (CL_CEC), according to cob frequency classes.

Table 5. Texture of fine earth (clay + silt + sand = 100%, in percentage by mass), of soils according to cob frequency classes.

Table 6. Estimation of soil availability for cob construction in Brittany, by volume, mass and proportion, estimation of consummation of the resource by heritage and orders of magnitude of potential cob resource provided by earthworks.

Figures with captions



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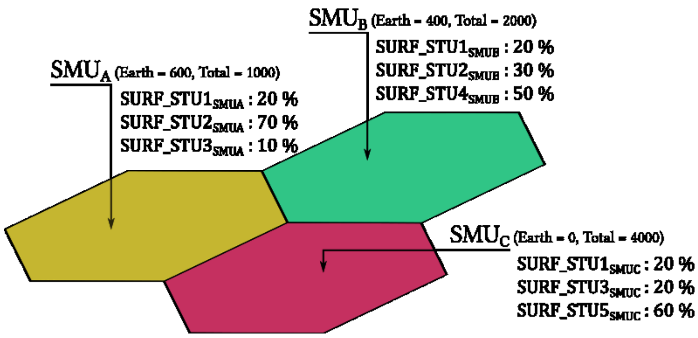

	STU$_1$		STU$_2$	
	TOT_STU	EARTH_STU	TOT_STU	EARTH_STU
SMU$_A$	200	120	700	420
SMU$_B$	400	80	600	120
SMU$_C$	800	0	0	0
Total	1400	200	1300	540
FREQ$_{STU}$	0.14		0.42	

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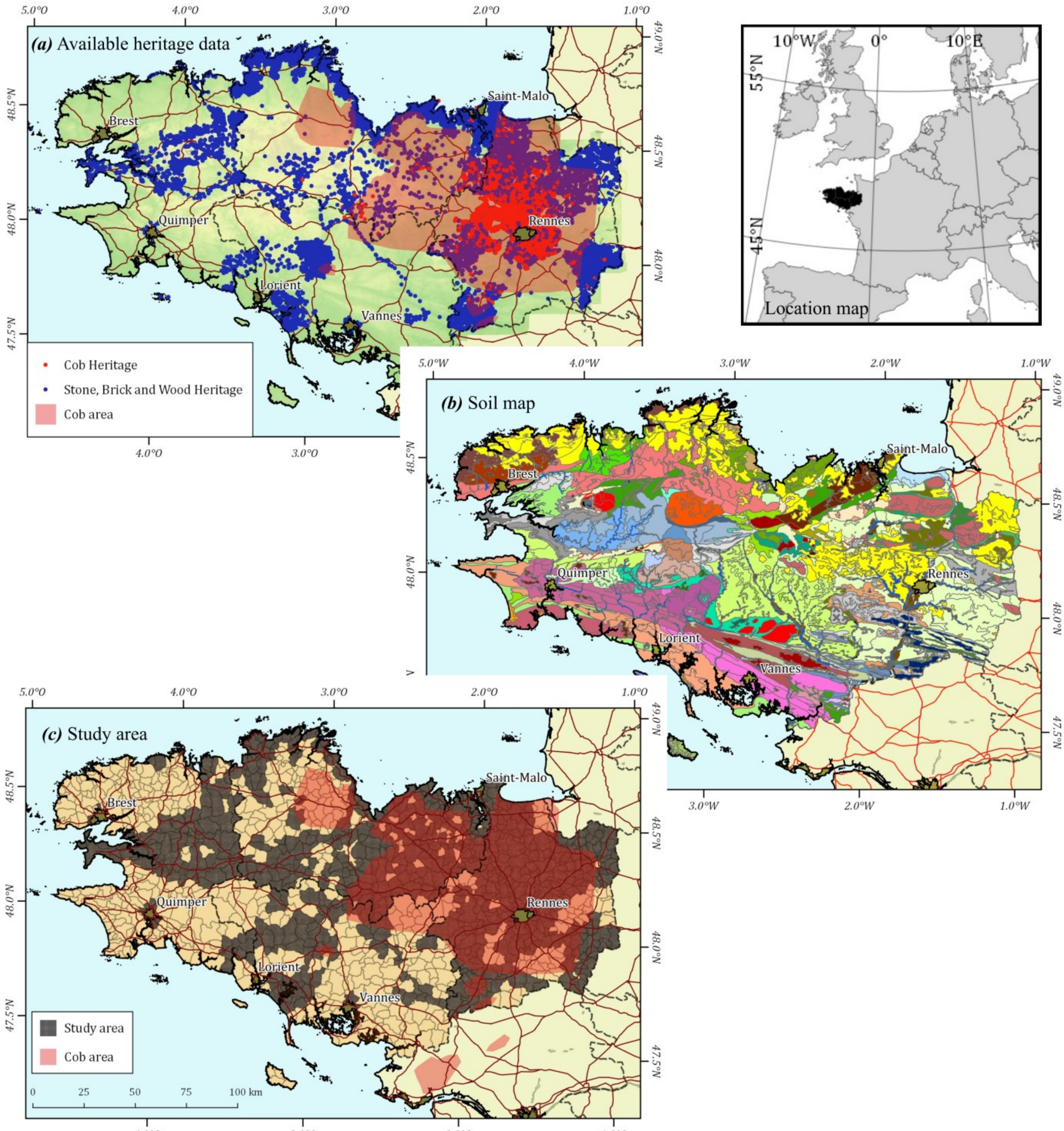

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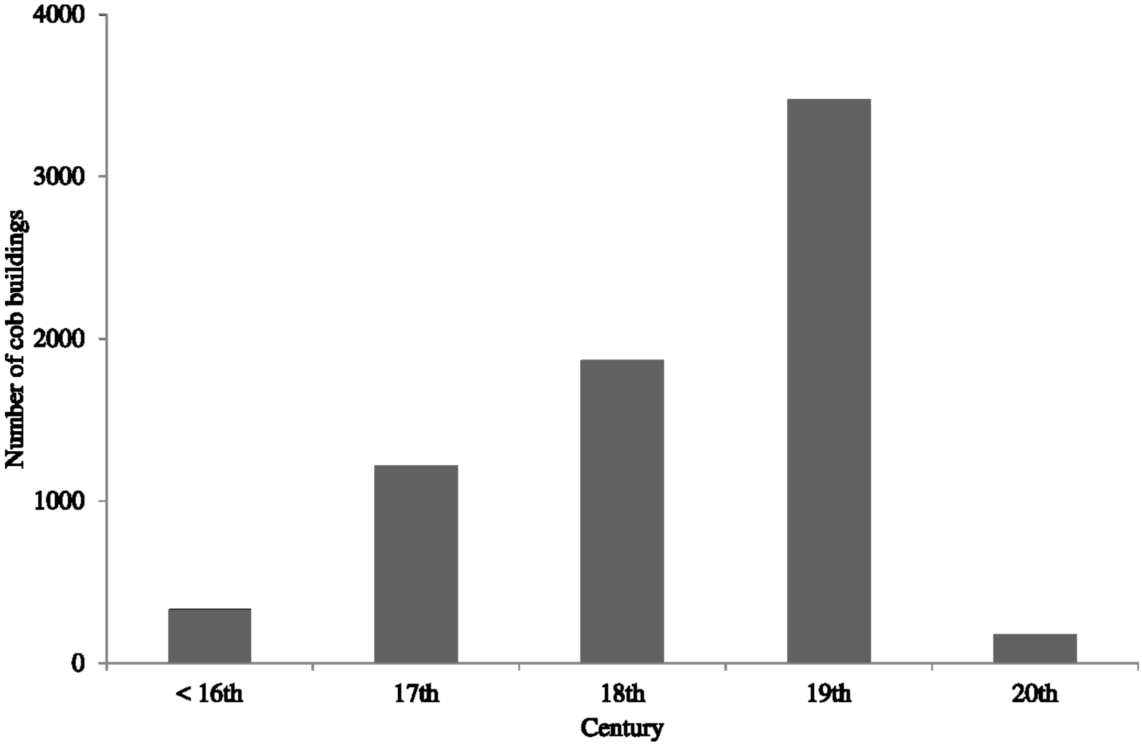

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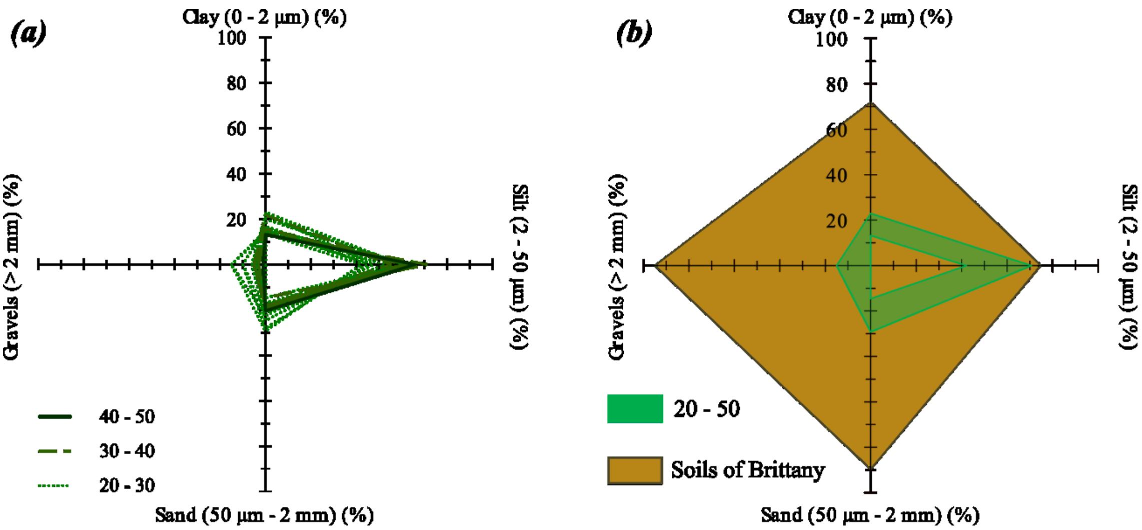

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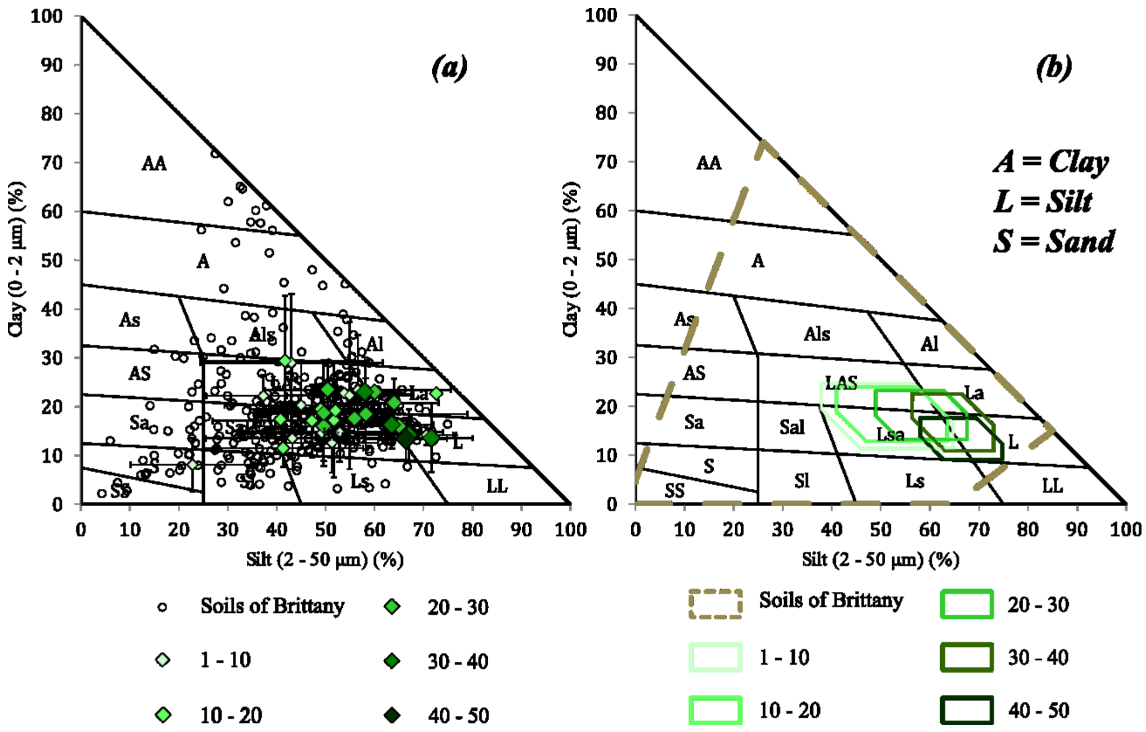

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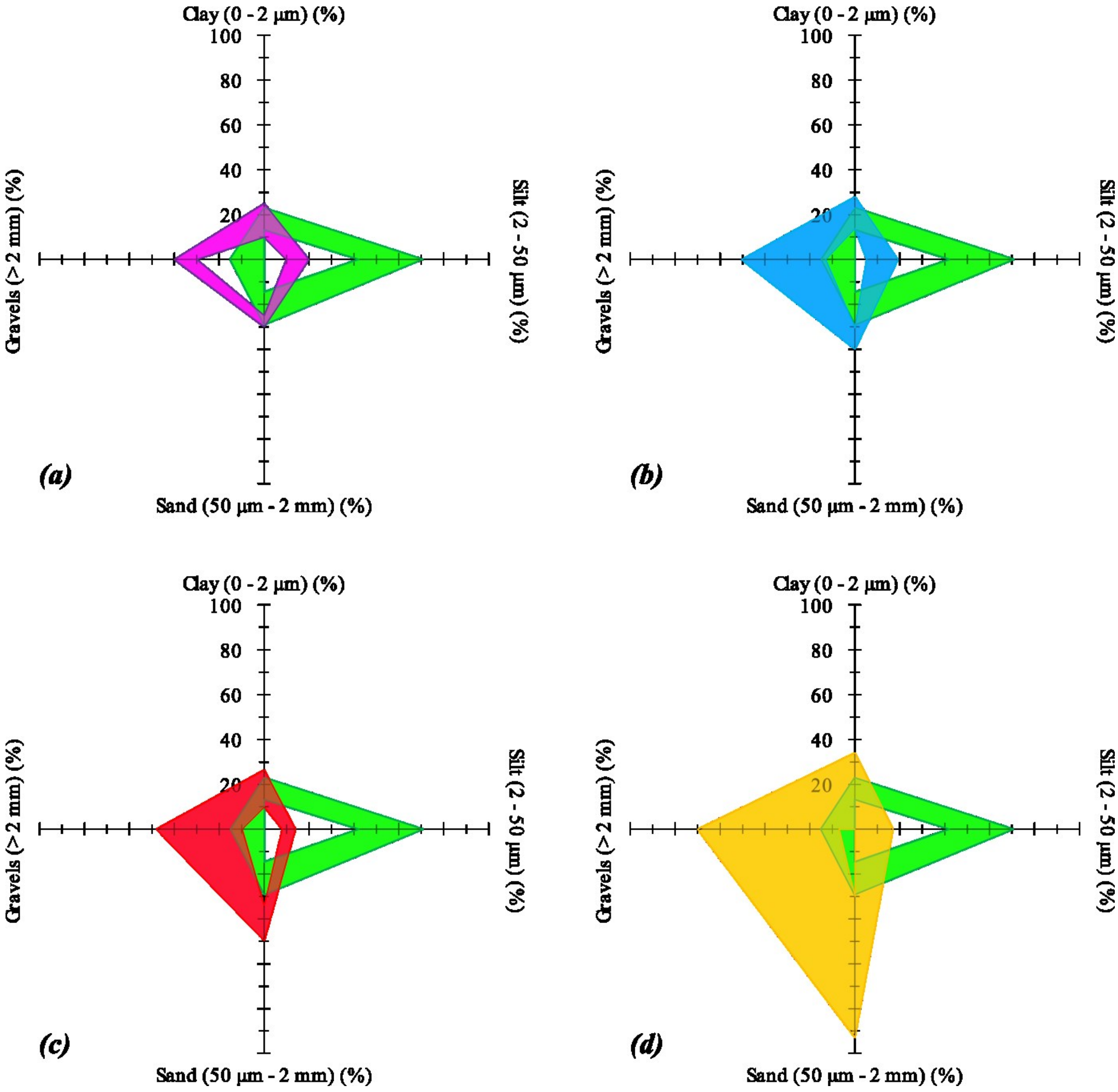

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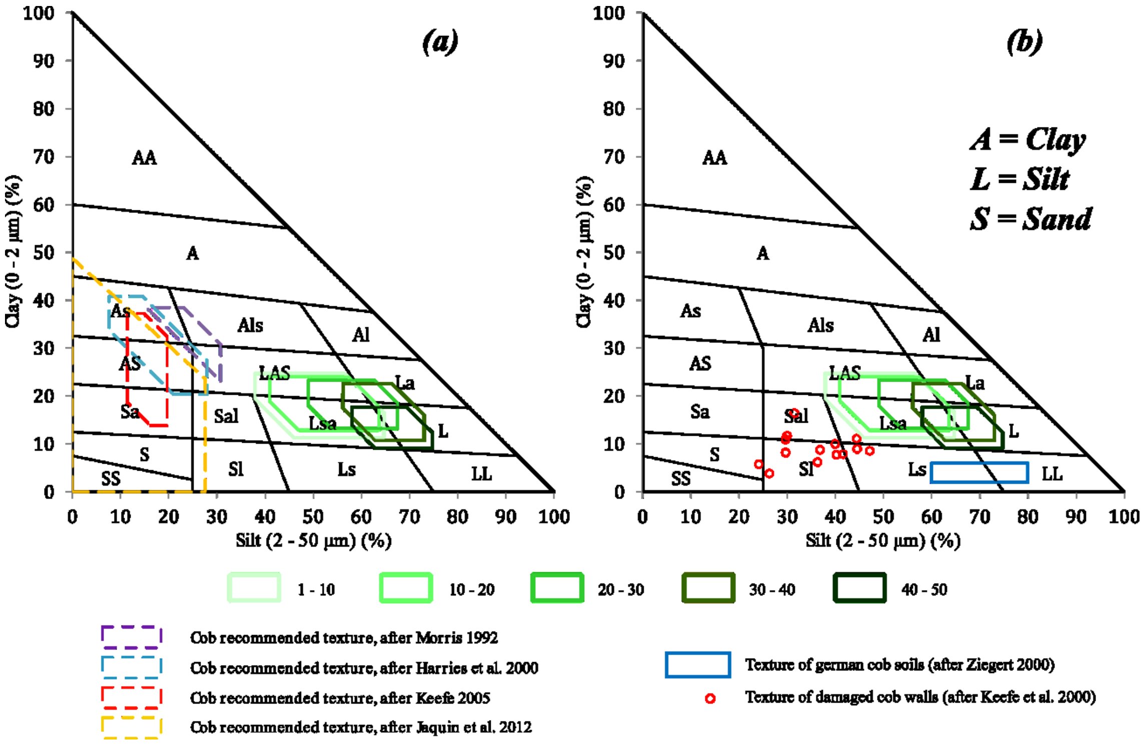

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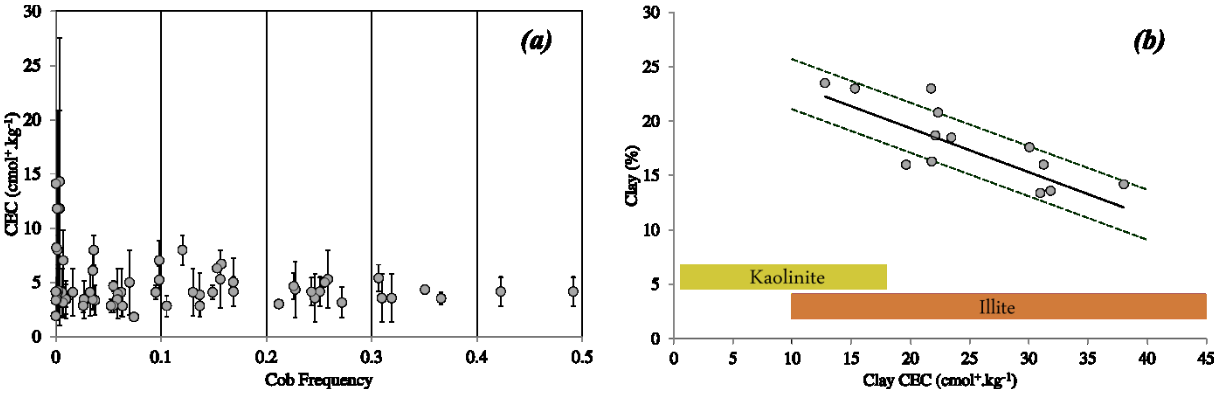

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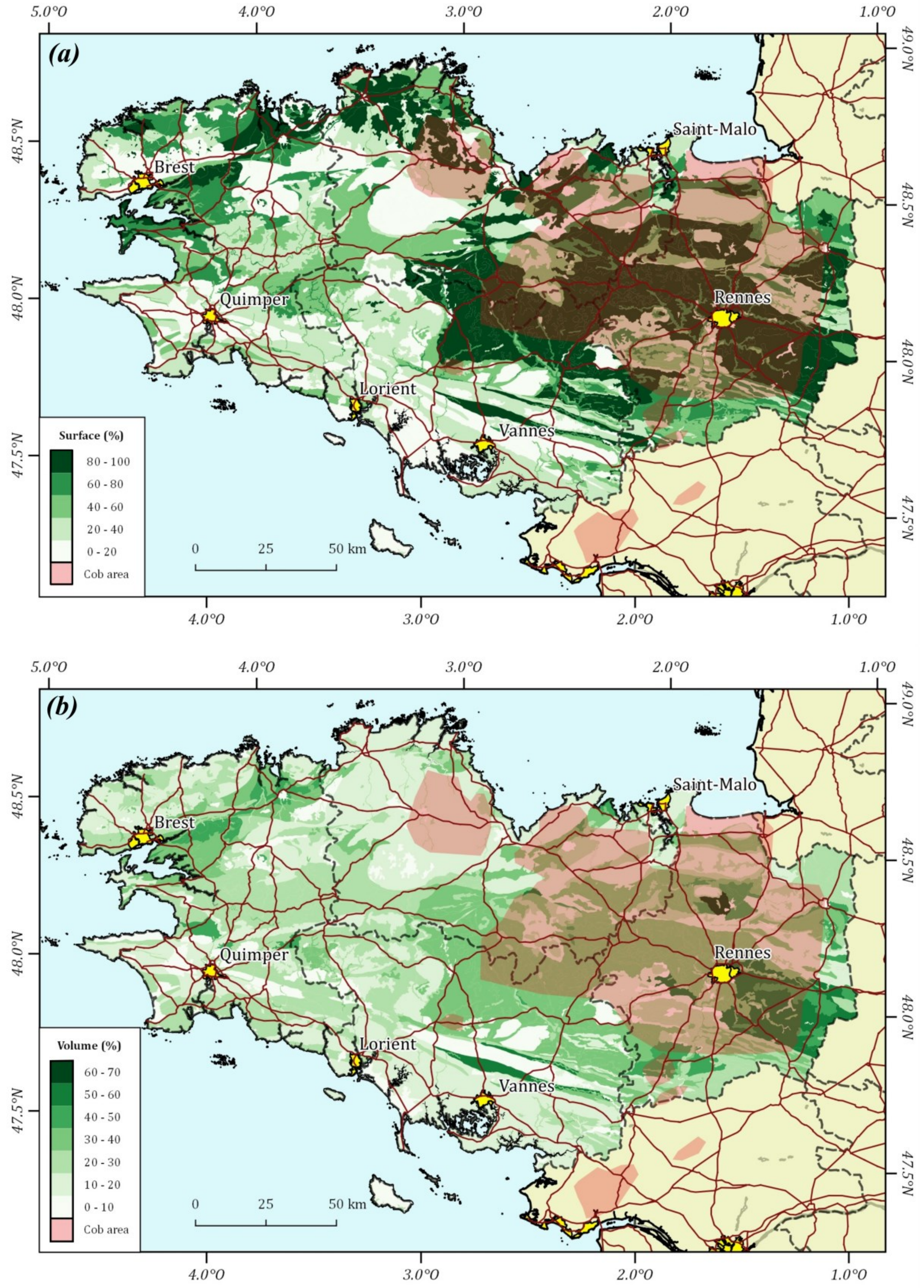

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Tables with captions

Table 1. Definition of parameters used for the determination of soil suitability

SMU	Soil Map Unit: spatially delineated polygon corresponding to a soil landscape, i.e. a collection of Soil Type Units
STU	Soil Type Unit: portion of the soil cover which has identical pedogenesis and, at any point in space, the same sequence of diagnostic horizons
$SURF\_STU_{SMU}$	Surface proportion of a STU in a SMU
TOT_SMU	Total number of heritage building of a SMU
TOT_STU	Total number of heritage building of a STU
$EARTH\_SMU$	Total number of earth heritage building of a SMU
$EARTH\_STU$	Total number of earth heritage building of a STU
$SURF\_STU_{SMUi}$	Proportion of surface of a STU in a SMU
$FREQ_{STU}$	Frequency of earth building heritage among the building heritage of a STU. This parameter describes the suitability of STUs with earth building
$FREQ_{STRATA}$	Frequency of earth building heritage among the building heritage of a Strata
σ_FREQ_{STU}	Standard deviation of the earth building frequency of a STU. A maximum standard deviation is set by the researcher to exclude outlier values
n_{STU}	Minimum total heritage building per STU. Only STUs with a number of total heritage building higher than n_{STU} are considered for the calculation
CHARACTER	Pedological characteristic (clay, silt, sand, gravel content and Cation Exchange Capacity)
CLASS	Class of frequency of earth building heritage (see Table 2)
$CONF\_INT_{STRATA}$	Estimation of the half-confidence interval of a pedological characteristic of a strata
$\overline{CHARACTER_{STRATA_j}\_CLASS_i}$	Average value of a pedological characteristic of a earth building frequency class
$\overline{CONF\_INT_{STRATA_j}\_CLASS_i}$	Average value of the confidence interval of each pedological characteristic of a earth building frequency class
$MIN_{CHARACTER\_}CLASS_i$	Minimum value of a pedological characteristic of a earth building frequency class
$MAX_{CHARACTER\_}CLASS_i$	Maximum value of a pedological characteristic of a earth building frequency class

Table 2. Frequency classes of earth buildings within STU.

Frequency *(FREQ)*	Frequency classes *(CLASS)* (%)
0.9 - 1.0	90 - 100
0.8 - 0.9	80 - 90
0.7 - 0.8	70 - 80
0.6 - 0.7	60 - 70
0.5 - 0.6	50 - 60
0.4 - 0.5	40 - 50
0.3 - 0.4	30 - 40
0.2 - 0.3	20 - 30
0.1 - 0.2	10 - 20
0.01 - 0.1	1 - 10
0.0 - 0.01	0 - 1

Table 3. Frequency, frequency class and standard deviation (σ_FREQ_{STU}) of Soil Type Unit (STU), calculated according to section2.1. Description of STUs can be found online: http://www.sols-de-bretagne.fr/ [30].

STU	*Cob frequency ($FREQ_{STU}$)*	*Frequency class (CLASS) (%)*	*Standard deviation (σ_FREQ_{STU})*
247	0.49	40-50	0.018
289	0.42	40-50	0.022
183	0.37	30-40	0.016
346	0.35	30-40	0.029
286	0.32	30-40	0.018
248	0.31	30-40	0.011
85	0.31	30-40	0.018
61	0.27	20-30	0.015
51	0.26	20-30	0.009
336	0.26	20-30	0.020
246	0.25	20-30	0.019
251	0.25	20-30	0.016
92	0.24	20-30	0.027
86	0.23	20-30	0.012
442	0.23	20-30	0.017
184	0.21	20-30	0.021
257	0.17	10-20	0.014
431	0.17	10-20	0.006
188	0.16	10-20	0.026
66	0.16	10-20	0.024
512	0.15	10-20	0.022
63	0.15	10-20	0.024
282	0.14	10-20	0.021
112	0.13	10-20	0.022
182	0.12	10-20	0.026
255	0.11	10-20	0.018
340	0.10	1-10	0.014
56	0.09	1-10	0.015
21	0.07	1-10	0.017
441	0.07	1-10	0.012
254	0.06	1-10	0.025
65	0.06	1-10	0.013
62	0.06	1-10	0.024
13	0.06	1-10	0.013
243	0.05	1-10	0.018
281	0.05	1-10	0.011
82	0.04	1-10	0.005
180	0.04	1-10	0.008
331	0.04	1-10	0.017
53	0.03	1-10	0.015
26	0.03	1-10	0.012
245	0.03	1-10	0.010
54	0.02	1-10	0.003
14	0.01	0-1	0.004
57	0.01	0-1	0.005
68	0.01	0-1	0.005
113	0.01	0-1	0.004
59	0.00	0-1	0.003
89	0.00	0-1	0.003
64	0.00	0-1	0.003
80	0.00	0-1	0.003
181	0.00	0-1	0.004
111	0.00	0-1	0.003
150	0.00	0-1	0.003
100	0.00	0-1	0.002
97	0.00	0-1	0.003
67	0.00	0-1	0.002
72	0.00	0-1	0.001
262	0.00	0-1	0.001
102	0.00	0-1	0.001
101	0.00	0-1	0.000
250	0.00	0-1	0.000
290	0.00	0-1	0.000

Table 4. Texture (in percentage by mass), Cation Exchange Capacity (CEC) of soils and Cation Exchange Capacity of clay fraction (CL_CEC), according to cob frequency classes.

Frequency class (%)	*Clay (0 - 2µm) (%)*		*Silt (2 - 50µm) (%)*		*Sand (50µm - 2mm) (%)*		*Gravel (>2mm) (%)*		*CEC (cmol$^+$.kg^{-1})*		*CL_CEC (cmol$^+$.kg^{-1})*
	Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Average*
40-50	9	17	57	74	13	28	0	2	2.8	5.5	31
30-40	11	22	54	70	10	25	0	9	2.8	5.3	26
20-30	12	22	46	63	13	31	0	20	3.0	5.5	24
10-20	12	22	37	58	17	37	0	21	3.6	6.2	28
1-10	10	21	32	55	16	36	2	30	3.0	5.4	25

Table 5. Texture of fine earth (clay + silt + sand = 100%, in percentage by mass), of soils according to cob frequency classes.

Frequency class (%)	*Clay (0 - 2µm) (%)*		*Silt (2 - 50µm) (%)*		*Sand (50µm - 2mm) (%)*	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
40-50	9	18	58	75	13	28
30-40	11	23	56	73	11	26
20-30	13	23	49	68	14	33
10-20	13	24	41	64	19	40
1-10	11	25	38	65	19	43

Table 6. Estimation of soil availability for cob construction in Brittany, by volume, mass and proportion, estimation of consummation of the resource by heritage and orders of magnitude of potential cob resource provided by earthworks.

Volume of soil identified as suitable for cob in Brittany (m^3)	6.8E+09
Mass of soil identified as suitable for cob in Brittany (t) [(1)]	8.8E+09
Proportion of soils of Brittany identified as suitable for cob (%)	23
Estimation of cob earth resource already consumed by cob heritage (%) [(2)]	0.03
Number of housing feasible, consuming the entire cob resource [(3)]	8.8E+07
Number of total housing in Brittany in 2013 [(4)]	1.8E+06
Resource consummation if all housing of Brittany were made of cob (%)	2.1
Landfilled soils suitable for cob in Brittany in 2012 (t) [(5)]	6.49E+05
Number of housing feasible, consuming suitable landfilled soils [(3)]	6490
Number of housing built in Brittany in 2013 [(4)]	12544
Cob potential market share in Brittany (%)	52

[(1)] *considering a soil density of 1.3 $t.m^{-3}$*
[(2)] *considering 30,000 buildings and 100 t per building*
[(3)] *considering 100 t per building as suggested by [13]*
[(4)] *source: INSEE*
[(5)] *considering 23 % of excavated soils, source: Cellule Économique de Bretagne*