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REVIEW

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A meta-analysis of carbon content and stocks in Technosols and identification of the main governing factors

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Abstract

Technosols, which are soils strongly impacted by human activity, are becoming increasingly common. To date, there has been little study of the share of the global soil carbon budget made up of carbon in Technosols or the contribution of Technosols to climate mitigation. A meta-analysis is proposed based on the analysis of 130 articles and consisting of the extraction of 953 observations on soil organic carbon (SOC) content of Technosols and related factors (e.g., climate, land use, nitrogen and bulk density). The mean SOC content of Technosols is 4.3% and SOC stock is 73.2 t C ha^{-1} for the 0–30-cm layer. The SOC content does not decrease significantly with depth and it shows high variability, even within the same depth layers. Climate has a significant effect on SOC content, especially in the upper soil layer. Land use (mainly urban, mining or industrial) shows a significant effect when considering all depths and is related to the nature of the constitutive artefacts. Unlike natural and agricultural soils, no correlation is observed with the depth nor the nature and presence of vegetation. This meta-analysis highlights the strong originality and diversity of Technosols, compared to other soils. Compared to other existing Reference Soil Groups, they are undoubtedly among the soils with the highest carbon stocks per unit area in the pedosphere.

Highlights:

- Technosols appear to be among the soils with the largest organic carbon stocks
- Mean value of soil organic carbon content in Technosols is 4.3%
- As for natural soils, the soil organic carbon in Technosols is influenced by climate
- Artefacts appear to be a major driver of organic carbon in Technosols

KEYWORDS

artefacts, carbon sequestration, soil organic carbon stocks, strongly anthropized soils

1 | INTRODUCTION

Soil is the biggest terrestrial carbon pool of the planet (Le Quéré et al., 2018; Scharlemann, Tanner, Hiederer, & Kapos, 2014). The increase of soil organic carbon (SOC) stocks has been identified as an effective means to mitigate the increase in atmospheric carbon dioxide (climate mitigation). It also plays a key role in improving soil fertility, ensuring food security and improving general soil resilience to global changes (Lal, 2004; Reeves, 1997; Stockmann et al., 2013). As a consequence, accurate, globalized and time-repeated measurements of SOC stocks are required to assess temporal and human-induced evolution of stocks.

To date, this monitoring has been carried out mainly for natural (Baritz, Seufert, Montanarella, & Van Ranst, 2010; Stockmann et al., 2015) and agricultural lands (Eve, Sperow, Paustian, & Follett, 2002), leaving aside environments that are more impacted by human activity. Human-impacted lands such as artificial lands, defined as lands removed from natural, agricultural or forest land cover (Béchet et al., 2017), already accounted for 4.2% of the surface of the European Union in 2015 (European Commission. Statistical Office of the European Union., 2017) and their surface increases continuously (average annual increase rate of urbanized areas varies, +5% year^{-1} to +10% year^{-1}; Dong, Zhuang, Xu, & Ying, 2008; Shalaby & Moghanm, 2015). Artificial land increase is a direct consequence of the Anthropocene, a geological era marked by human activities and its effects on the biosphere and lithosphere (Ellis & Ramankutty, 2008; Geisen, Wall, & van der Putten, 2019). With a pedological entry, a high portion of the soils encountered in artificial lands is strongly impacted by human activities (e.g., urban, mining and industrial; Béchet et al., 2017) and should be gathered under the term Technosols (IUSS Working Group WRB, 2014). More precisely, Technosols are defined as containing at least 20% of artefacts in their upper 100 cm. Artefacts refers to materials that have been created, substantially modified or brought to the surface by humans. The most frequent artefacts are: construction debris, mine spoil and industrial waste, but also technic hard material (e.g., asphalt and bitumen) and geomembranes (Lehmann, 2006). Technosols encompass a wide variety of situations and are strongly heterogeneous, notably in terms of level of anthropization (Blume, 1989; Morel, Chenu, & Lorenz, 2015; Novák, Balla, & Kamp, 2020; Quintela-Sabarís, 2019). It is therefore important to stress that Technosols are not only found in artificial land, and that soils in artificial land are not only Technosols. Such a complex assessment of their worldwide spatial distribution has led to their exclusion from worldwide soil carbon budgets (FAO, 2018).

However, high SOC stocks have been reported in various Technosols: (a) in a constructed Technosol for the reclamation of industrial brownfields with 190 t C ha^{-1} in the first 30 cm (Rees et al., 2019), (b) in industrial settling ponds with 165 t C ha^{-1} in the first 30 cm (Huot et al., 2013), and (c) in urban soils from Paris and New York City with 99 and 113 t C ha^{-1}, respectively, in the first 30 cm (Cambou et al., 2018). High sequestration rates have also been recorded in an industrial constructed Technosol at about 3 t C ha^{-1} year^{-1} (Rees et al., 2019) and in reclaimed mine soils at up to 1.85 t C ha^{-1} year^{-1} (Ussiri & Lal, 2005), notably in the first 30 cm. High sequestration phenomena have also been recorded in buried technogenic horizons (16–21 to 28–34-cm horizons) made of marble waste (3.6 t C ha^{-1} year^{-1}; Simón, García, Sánchez, & González, 2018).

Technosols thus appear to be neglected but possibly significant contributors to global soil carbon stocks and storage as they could represent both large areas of soils with high carbon stock per unit area and soils with high sequestration rate. The aims of this study are first to finely describe and quantify the range of carbon contents and stocks in soils with a strong human influence and also to explore the main factors governing their carbon content in comparison with other soils. Given the great diversity of Technosols, we propose here a generic bibliographic methodology of data collection and analysis. The published data on SOC contents and SOC stocks in Technosols, covering a wide range of situations, are compiled. The resulting database is then analysed in order to identify the main governing factors of SOC contents or stocks. The role of artefacts in carbon dynamics and the potential of carbon sequestration of such soils are then discussed.

2 | MATERIALS AND METHODS

2.1 | Data collection

The first step is to identify and collect the target publications, that is, those giving quantitative indication of carbon content or stocks in Technosols. They were obtained with a search request using Equation (1) for peer-reviewed published articles in the Web of Science citation database:

$$TS = (Technosol^{*}\ AND\ (organic\ carbon\ OR\ organic\ matter)), \tag{1}$$

where *TS* is the ‘topic’ of the article, which includes title, keywords and abstract. The material used in this article corresponds to a search conducted in February 2019. In order to assess the representativeness of our corpus, it was supplemented by the following research equations:

$$TS = (\textit{Industrial soil}^{*}\ AND\ (\textit{organic carbon OR organic matter})) \quad (2)$$

$$TS = (\textit{Urban soil}^{*}\ AND\ (\textit{organic carbon OR organic matter})) \quad (3)$$

$$TS = (\textit{Mine soil}^{*}\ AND\ (\textit{organic carbon OR organic matter})) \quad (4)$$

2.2 | Data extraction

For each article, information on observations was collected and organized in an excel file, each line corresponding to a different observation. Observations can be either a soil sample, taken from a soil profile or as part of an experimental plan, or an anthropogenic amendment (applied to a soil) or an artefact (isolated from the Technosol in which it should be found). Observations of upper layers described as non-soil layers (such as litter layers) by the authors were not included.

For each observation the following data were collected, when available: country of the studied soil, land use, soil cover, climate, soil type (IUSS Working Group WRB, 2014), soil principal qualifier (IUSS Working Group WRB, 2014), age of the soil (starting from the end of the anthropic activity or from the Technosol's formation), mean annual temperature (explicitly mentioned or determined based on the location), mean annual rainfall (explicitly mentioned or determined based on the location), upper and lower limits of soil horizons, depth of sampling (averaged to calculate the average sampling depth), soil organic carbon (SOC) content, soil organic matter (SOM) content, total carbon (TC) content, nitrogen (N) content, pH, cation exchange capacity (CEC), bulk density and texture (clay, silt and sand contents).

Complementary typologies are defined for the following information:

- land use: industrial, urban, mining, archaeological, agricultural, other land uses;
- soil cover: bare, shrubland, grassland, crop, forest; and
- climate (according to the five main Köppen-Geiger climate classes): tropical, dry, temperate, continental, polar (Peel, Finlayson, & McMahon, 2007).

For SOC, SOM, TC, N, pH, CEC, bulk density and texture, measurement methods are also recorded, as well as statistical related data: number of analytical repetitions and standard deviation.

When SOC information is missing, a proxy value is used. SOM is converted using the 0.58 conversion factor (applied on 14% of the data). When both SOM and SOC are missing, TC is used as the SOC value, after checking that the soils are not carbonated (17% of the data). We define the SOC* variable to compile SOC data and proxies obtained from SOM or TC. Then, when the SOC* is 0%, it is arbitrarily set to 0.1%, which is considered to be the standard limit of quantification (LOQ) for the dry combustion method (Beltrame et al., 2016). This change (0–0.1%) is carried out for 15 data over 1,394.

All collected information is stored in a database available at: https://doi.org/10.24396/ORDAR-60. In the Results section, only observations concerning soil samples identified as Technosols are analysed. Data related to anthropogenic amendments, artefacts or other soil types (often used as a control) are not presented.

2.3 | Soil organic carbon stock calculation

Soil organic carbon stock (SOC stock) in the 0–30-cm soil upper horizon is calculated using the following formula (Poeplau, Vos, & Don, 2017):

$$\textit{SOC stock}_{0-30\,cm} = \textit{SOC}^{*}{}_{0-30\,cm} \times \textit{bulk density} \times \textit{thickness} \quad (5)$$

where $\textit{SOC stock}_{0-30\,cm}$ is the SOC stock of the Technosol between 0 and 30 cm, in t C ha^{-1}, $\textit{SOC}^{*}{}_{0-30\,cm}$ is the SOC* content for observations with an average sampling depth between 0 and 30 cm, in % (or more precisely, g 100 g^{-1} of dry weight of soil), bulk density is the bulk density of the soil at the same average sampling depth, in g cm^{-3}, and thickness is the thickness of the soil layer considered, in cm (here 30 cm). SOC* is preferred to SOC to increase the number of available observations.

2.4 | Data analysis

For quantitative data, correlation coefficients are assessed using pairwise complete observations.

The relationship between SOC content and average sampling depth is analysed by testing two of the most widely used models in soil science: an exponential relationship (Equation (6)) and a log–log relationship (Equation (7)) (Jobbágy & Jackson, 2000; Meersmans, van Wesemael, De Ridder, & Van Molle, 2009; Mishra et al., 2009; Zinn, Lal, & Resck, 2005):

$$SOC^* = a\,e^{-b \times D}, \tag{6}$$

$$\log(SOC^*) = c\log(D) + d, \tag{7}$$

where *SOC** is the compiled data, D is the average sampling depth, and *a*, *b*, *c* and *d* are parameters of the models. Parameters are estimated by a nonlinear (weighted) least-squares algorithm (nonlinear least squares function 'nls' of R software; R Core Team, 2020).

The impact of qualitative variables such as climate, land use, soil cover and World Reference Base for Soil Resources (WRB) principal qualifier on SOC* is assessed by ANOVA, followed by a pairwise *t*-test with Bonferroni correction if conditions are met (also achieved with R software; R Core Team, 2020).

Boxplots are used to figure data distribution: the band inside the box represents the median, black line red diamond represents the mean, left and right ends of the box represent the first and third quartile, respectively, the whiskers indicate the lowest datum within 1.5 interquartile range of the lower quartile, and the highest datum within 1.5 interquartile range of the upper quartile. Different letters indicate significant differences ($p < 0.05$).

3 | RESULTS

3.1 | Dataset description

Our research equations resulted in 130, 1,956, 2,478 and 2,445 articles for Equations (1) to (4), respectively. The number of articles corresponding to the four research equations has been constantly increasing over the years from 2012. Over the last 11 years (2008–2018), the average increase of published articles is of 51, 11, 11 and 13% per year for Equations (1) to (4), respectively (Figure 1).

In this work we propose to focus on the results of Equation (1) only, that is, 130 articles. Overall, the dataset contains 953 observations of Technosols. The percentage of recovered data varied widely from 10.8% for SOM to 99.3% for land use, or 76.9% for sampling depth (the most recovered numerical data; Figure 2). Qualitative variables are the most recovered ones, except for the soil WRB principal qualifier.

The soil organic carbon content is available for 50.5% of the observations. The SOC* variable is available for 72.1% of the database observations (i.e., 687 data over 953). Information on bulk density remains scarce (14.9%; i.e., 142 pieces of data). Only 74 observations provide both SOC* and bulk density, thus limiting SOC stocks analysis.

3.2 | Origin of the data and age of the Technosols

The dataset covers observations across all types of climate, although temperate and continental climates are the most represented (46% and 35% of the data, respectively). A dry climate is in third place, with 137 pieces of data (15%), and tropical and polar climates are associated with 23 (2%) and 17 (2%) pieces of data, respectively. These last three climatic situations (dry, tropical and polar) have appeared quite recently in studies on Technosols, with a first occurrence in 2012 for dry, in 2014 for polar and in 2015 for tropical climates.

As for climate, all continents are represented in our dataset. The European region is by far the strongest contributor of data on Technosols (78%, 737 pieces of data). The highest contributors are European countries, with

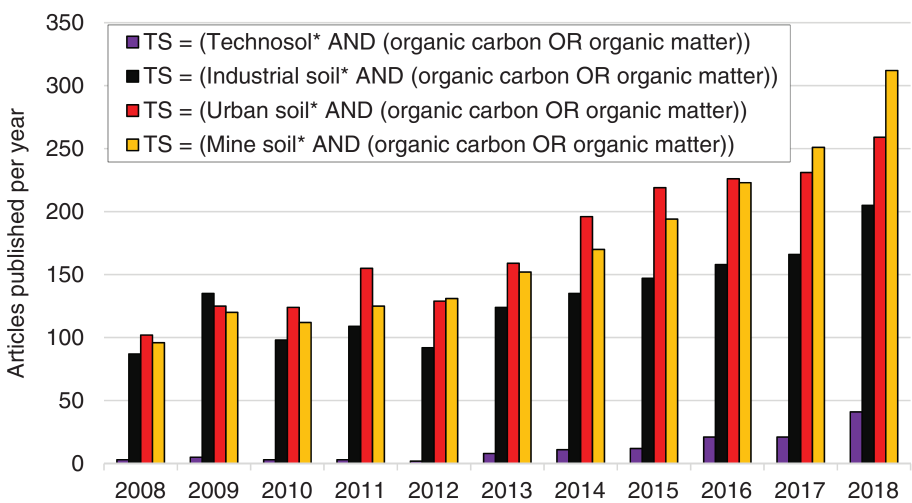

FIGURE 1 Evolution of number of articles published per year over the period 2008–2018 based on our four research equations [Color figure can be viewed at wileyonlinelibrary.com]

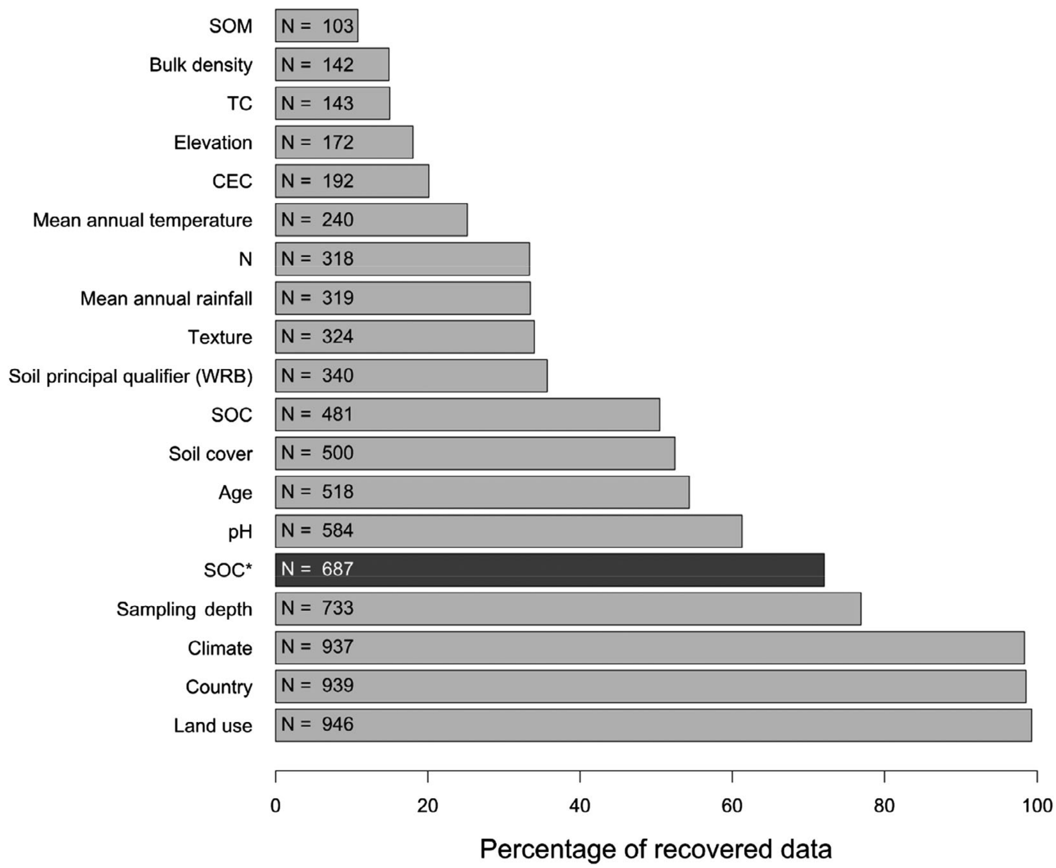

FIGURE 2 Data completeness (of the 953 observations concerning Technosols). CEC, cation exchange capacity; SOC, soil organic carbon; SOM, soil organic matter; TC, total carbon; WRB, World Reference Base for Soil Resources

Spain, France and Poland being associated with 206, 188 and 166 observations, respectively, that is, almost 60%. The European region is followed by Asia (15%, 138 pieces of data), then Africa, Australia, and North and South America (between 13 and 19 pieces of data). The dataset includes observations from 29 different countries.

Regarding soil age, most of the observations concern young soils, with a median age of 6 years. Mean soil age is much higher at 29 years, due to the contribution of aged soils (e.g., 300 and 400-year-old soils, from a charcoal production site and post-mining site) (Ciarkowska, Gargiulo, & Mele, 2016; Hirsch, Schneider, Bauriegel, Raab, & Raab, 2018).

3.3 | SOC* content and SOC* stock distribution

SOC* content distribution (part (a) of Figure 3) and SOC* stock distribution (calculated with Equation (5); part (b) of Figure 3) are represented. Mean SOC* content is 4.29%, whereas the median is 1.63%, the first quartile is 0.59% and the third quartile is 4.71%. Standard deviation associated with SOC* content is 7.45%. Maximum SOC* content is 48.7%; it relates to a deep horizon (175–185 cm) of industrial soil that includes coal and slag fragments (Coussy et al., 2017). The high difference between mean and median is explained by a high quantity of values above 10% of SOC*: 66 data over the 687 (9.6% of the data).

The distribution of SOC* stock is similar to the distribution of SOC*: the mean (73.2 t C ha^{-1}) is higher than the median (42.6 t C ha^{-1}). The third quartile (90.6 t C ha^{-1}) is close to the mean. The maximum SOC* stock is 280 t C ha^{-1}; it relates to an industrial soil (close to a steelmaking plant; Kanbar, Srouji, Zeidan, Chokr, & Matar, 2018). Eight data exceed 200 t C ha^{-1}over the 76 data (10.5%).

3.4 | Relation of SOC* content with other quantitative variables

SOC* content is correlated with few other variables. It is positively correlated with nitrogen content (correlation coefficient = 0.71) and negatively with bulk density

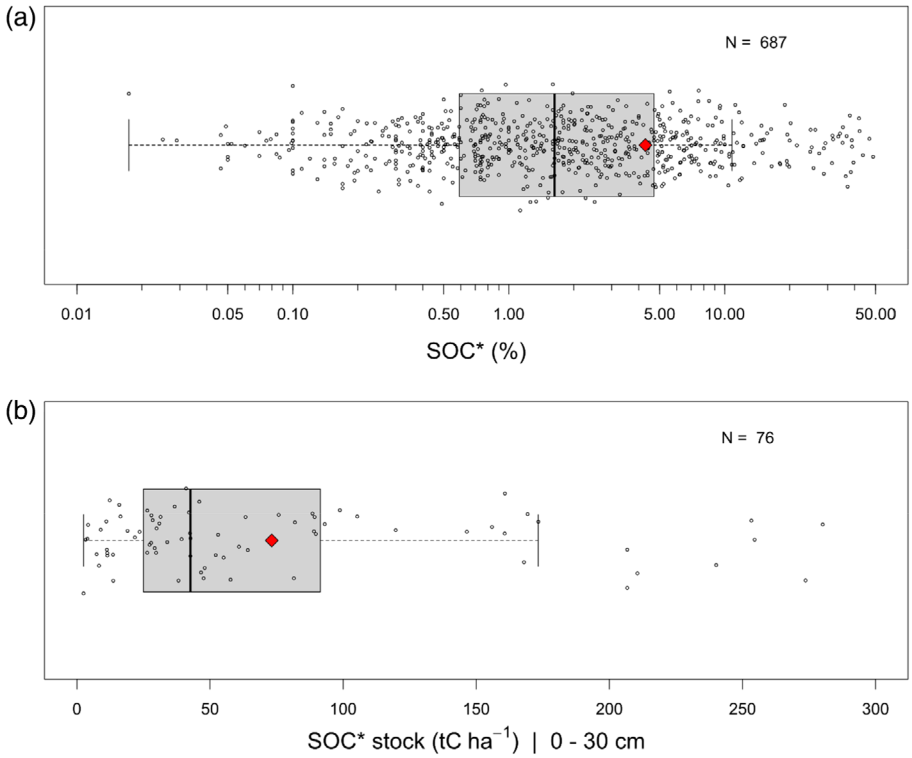

FIGURE 3 Distribution of SOC* content (a) and SOC* stock (b) of Technosols collected and calculated from the meta-analysis. Logarithmic scale is used in the boxplot (a) for a better visualization of low value data. SOC, soil organic carbon [Color figure can be viewed at wileyonlinelibrary.com]

(−0.48) and mean annual temperature (−0.31). The correlation coefficient with other variables (pH, CEC, clay, silt or sand content, sampling depth, age, mean annual rainfall) has an absolute value lower than 0.20.

The C/N ratio, a classical indicator of soil fertility, has a mean value of 28.6 and a median at 11.8 with a standard deviation of 46.2. The linear regression between SOC* and N gives a slope of 13.01 (310 observations).

3.5 | Depth distribution of SOC*

There are 530 observations represented in part (a) of Figure 4: more than 78% of the SOC* data is accompanied by data on the sampling depth. Observations are mainly located in the first decimetres of soils (50% of the observations have an average sampling depth between 0 and 16 cm). The number of observations decreases with depth. Observations are unevenly distributed with depth: 46% of the observations have SOC* between 0 and 10% and average sampling depth between 0 and 20 cm, whereas this area covers 2% of the graph. Conversely, fewer than 4% of the observations have SOC* over 10% and average sampling depth over 20 cm, whereas this area covers 72% of the graph.

SOC* content seems to decrease slightly with depth, even though it has been shown before that the correlation between SOC* content and depth is tight (correlation coefficient = −0.10). Part (b) of Figure 4 shows the distribution of SOC* content for five classes of average depths of sampling in the form of boxplots. Mean SOC* content is 7.3 ± 10.5% in 0–10 cm, 2.7 ± 2.8% in 10–30 cm, 2.5 ± 5.7% in 30–60 cm, 3.4 ± 4.8% in 60–100 cm and 7.9 ± 13.6% in 100–200 cm (mean ± standard deviation). Considering these five classes, mean SOC* content decreases from 0–10 cm to 10–30 cm, then reaches a plateau up to 30–60 cm, before increasing sharply in the deepest horizons to reach a mean SOC* content comparable to the 0–10-cm horizon. The median is systematically lower than the mean; its value is 0.2 to 0.7 times that of the mean; the first quartile is also systematically closer to the median than the third quartile, which indicates that the SOC* data are concentrated towards the low SOC* content values. Each class still contains high SOC* content values that pull the mean upwards.

The data systematically show very high variability, with the standard deviation (*SD*) varying from 1 to more than 2 times the value of the mean for the different depth classes studied. Models shown in the left part of Figure 5 reach a very low coefficient of determination (R^2): 0.10 and 0.11 for the exponential model and log–log model, respectively. High SOC* content values are not well predicted for average sampling depths above approximatively 10 cm, as well as low SOC* content values for data under 10 cm of average sampling depth. Failure in modelling depth distribution of SOC* content (low R^2) must be related to the high data dispersion. Overall, exponential and log–log models tend to

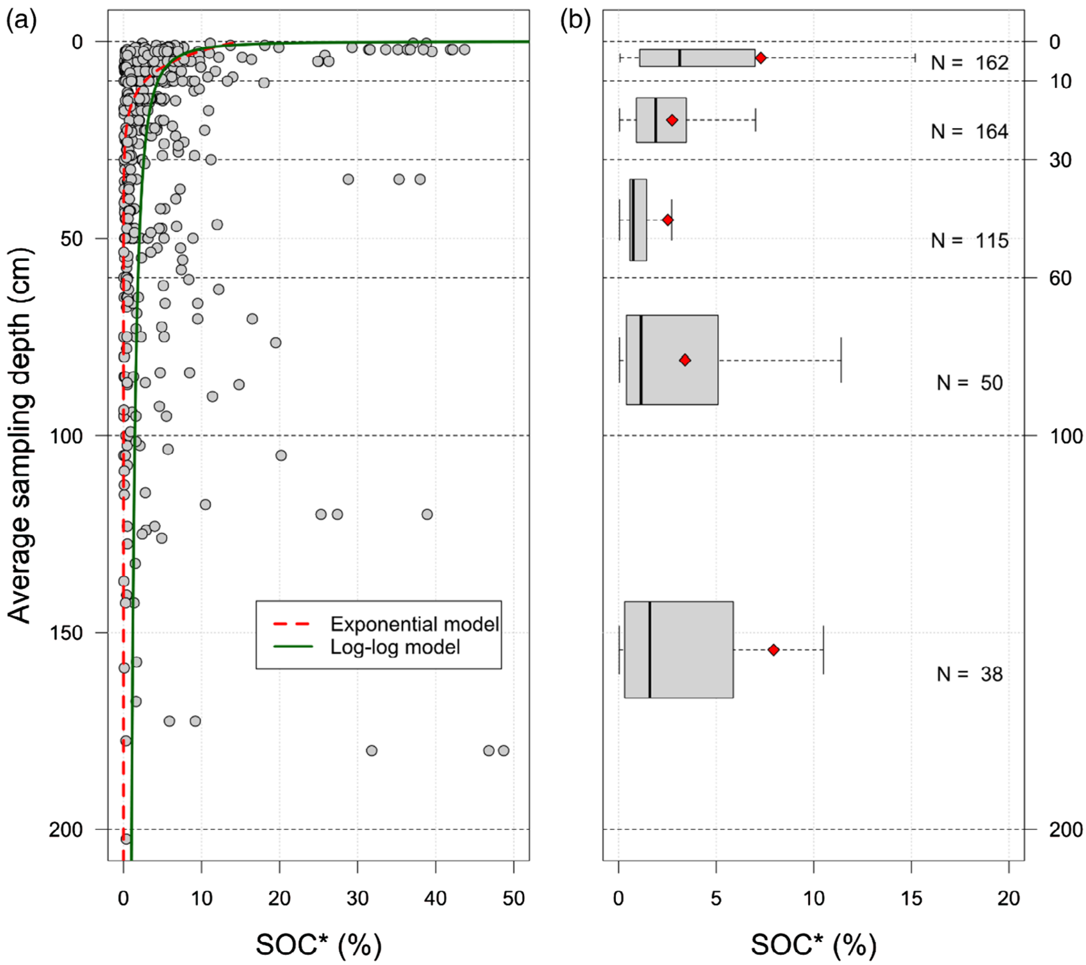

FIGURE 4 Depth distribution of SOC* content and fitted models (a) and boxplots of SOC* content for 0–10 cm, 10–30 cm, 30–60 cm, 60–100 cm and 100–200 cm of average sampling depth (b). SOC, soil organic carbon [Color figure can be viewed at wileyonlinelibrary.com]

underestimate SOC* content values (mean SOC* content of predicted values is 2.6% and 4.0%, respectively, against 4.3% for observed values).

Special attention has been paid to low and high SOC* content values. Eighteen percent of the observations have SOC* content lower than 0.5%. Above 60% of the observations that have an SOC* content lower than 0.5% with recorded land use are observations of mining land use.

High contents of SOC* are reported at various depths: 18 observations have SOC* content higher than 20% between 0 and 10 cm of average sampling depth, and nine more observations have SOC* content higher than 20% at above 35, 120 and 180 cm average sampling depth (three observations each). These nine last observations concern industrial soils from Coussy et al. (2017). It is worth noting that the maximum SOC* content value of this graph is encountered at 180 cm average sampling depth. Fifty percent of observations with SOC* content higher than 20% with recorded land use are observations of industrial land use. For dependency considerations, it is worth noting that there were only 1.7 ± 2.3 observations by soil profile on average, with a median of 1, which means that most of the observations were from isolated soil profiles.

3.6 | Other influencing factors

3.6.1 | Climate

The effect of climate on the SOC* content of the topsoil (between 0 and 30 cm) of the studied Technosols is shown in Figure 5. Globally, there is a significant effect of climate on SOC* (p-value of 0.0023) according to the following ranking: polar (1.83 ± 0.75%, mean ± standard deviation) ≈ dry (1.87 ± 2.14%) ≈ tropical (1.97 ± 1.83%) < temperate (4.48 ± 5.40%) < continental (6.64 ± 10.30%). As an illustration, data with SOC* content over 10% are only encountered in temperate or continental climates. Data still show a very high variability inside the different classes.

Application of the same statistical treatments on the upper horizon of Technosols only (i.e., soils with an upper limit of sampling depth equal to 0 cm), instead of the previous 0–30-cm surface horizons, leads to even stronger differences: ANOVA's test *p*-value is 1.77×10^{-6}, and there is an additional significant difference, between SOC* in continental climate and in temperate climate. Conversely, if all sampling depths are considered, ANOVA's test *p*-value is higher: 0.0151.

3.6.2 | Soil cover

The differences in SOC* content between the different soil covers are much smaller than those between climates, the ANOVA test gives a *p*-value of 0.6311 (all depths considered, other depth considerations were close). No statistical difference nor obvious trend are observable. The SOC* content is slightly higher in croplands if considering all depths (4.4% SOC* in croplands

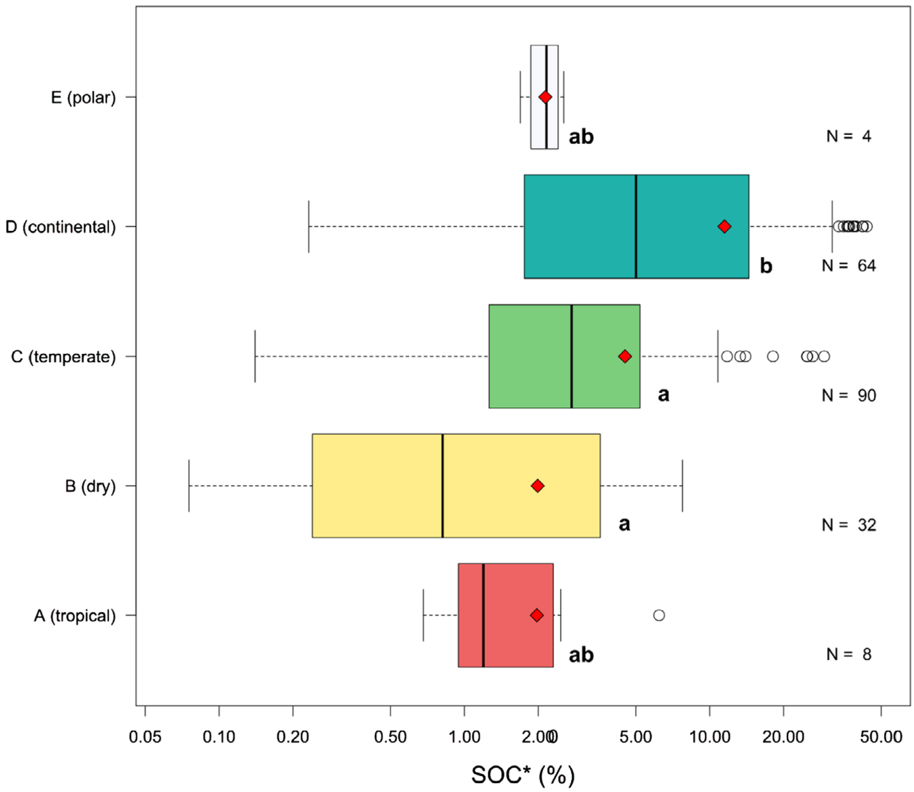

FIGURE 5 Influence of climate type (according to Köppen-Geiger classification) on SOC* content for Technosols with average sampling depth between 0 and 30 cm. Logarithmic scale is used in the boxplot for a better visualization of low value data. SOC, soil organic carbon [Color figure can be viewed at wileyonlinelibrary.com]

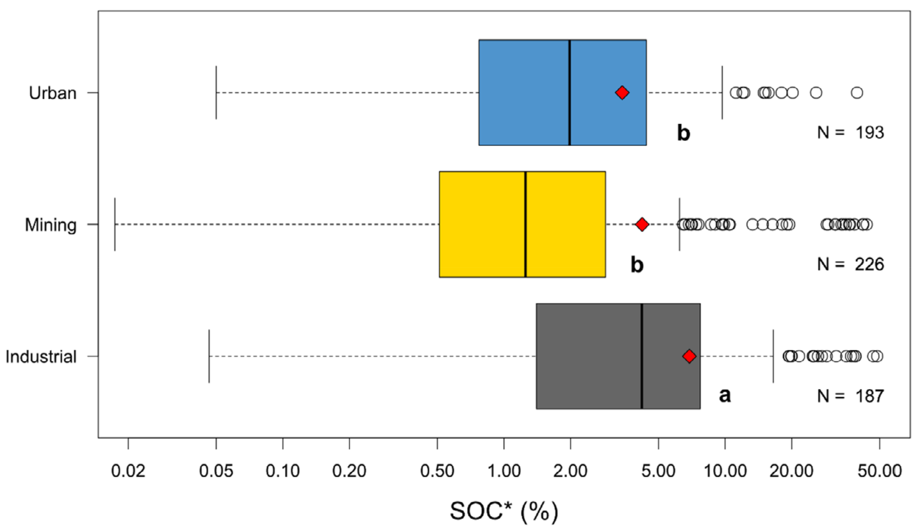

FIGURE 6 Influence of land use on SOC* content in Technosols. Logarithmic scale is used in the boxplot for a better visualization of low value data. SOC, soil organic carbon [Color figure can be viewed at wileyonlinelibrary.com]

against 4.1, 3.7 and 3.0% in grasslands, forests and bare soils, respectively) but croplands SOC* content is lower than that of other soil covers if considering 0–30-cm average sampling depth (3.2% SOC* in croplands against 4.2, 4.8 and 4.7% in grasslands, forests and bare soils, respectively).

3.6.3 | Land use

The effect of land use on SOC* content is shown in Figure 6. Only urban, mining and industrial land uses are discussed hereafter as they are highly dominant: 54 pieces of data mentioning an archaeological land use (from two articles: Vittori Antisari, Cremonini, Desantis, Calastri, & Vianello, 2013; Itkin, Crouvi, Curtis Monger, Shaanan, & Goldfus, 2018), three pieces of data mentioning an agricultural land use, and 24 pieces of data with unidentified land uses.

Urban, mining and industrial land uses data are quite equally represented (193 pieces of data for urban, 226 for mining and 187 for industrial land uses). There is a significant effect of land use on SOC* content; ANOVA's test p-value is 2.69×10^{-5}. A significant difference is also found when topsoil only is considered. Industrial soils show significantly higher SOC* content than mine and urban soils. Overall ranking may be: mine soils < urban soils < industrial soils, according to quartiles and median rankings. The mean (± standard deviation) of SOC* content is $3.4 \pm 4.5\%$ for urban Technosols, $4.2 \pm 8.5\%$ for mine Technosols, and $6.9 \pm 9.1\%$ for industrial Technosols. The variability is almost two times less important in urban soils than in other land uses. Urban soils notably display fewer outliers (circles in Figure 6): only 10 pieces of data are reported over the 1.5 interquartile range of the upper quartile for urban soils, against 33 for mine soils and 19 for industrial soils.

When considering the highest SOC* content soils, among the 10 outliers of urban soils, three concern soils formed on buildings (named Edifisol, Markiewicz, Hulisz, Charzyński, & Piernik, 2018), two concern constructed soils made of bricks and compost of green wastes and sewage sludge (Vidal-Beaudet, Rokia, Nehls, & Schwartz, 2018; Yilmaz et al., 2018), and five concern Reductic Technosols formed above municipal wastes or sanitary landfill, or sewage sludge-amended soil (Blume & Felix-Henningsen, 2009).

Among the 33 outliers of mine soils, 10 pieces of data concern former lignite mine soils (Greinert, Drab, & Sliwinska, 2018), two concern biochar and biomass-amended copper-molybdenum-gold tailings (You, Dalal, & Huang, 2018), four concern an organic amended mine soil (Rodríguez-Vila, Forján, Guedes, & Covelo, 2017), five concern former tin, zinc, lead and gold mines surface layers (Pascaud et al., 2017), two concern copper/lead-zinc mine tailings amended with sugarcane residues and compost (Yuan, Xu, Baumgartl, & Huang, 2016), four concern old soils of restored zinc and lead mining sites (Ciarkowska et al., 2016), four concern hard coal and pyrite mine soils (Uzarowicz & Skiba, 2011) and two concern sludge and ash-amended soils developed on copper mine tailings (Asensio Fandino, Andrade Couce, Alonso Vega, & Fernandez Covelo, 2010).

Among the 19 outliers of industrial soils, four pieces of data concern soils developed in an ash settling pond (Uzarowicz, Kwasowski, Spiewak, & Switoniak, 2018), 13 concern different horizons of a Technosol made of smelter slags (containing high amounts of coal, Coussy et al., 2017; Dagois et al., 2016), and two concern fly ash-enriched soils (Hartmann, Fleige, & Horn, 2010).

3.6.4 | WRB principal qualifier

The soil WRB principal qualifier is poorly reported in articles (only 35.7% of all data [340 pieces of data, cf. Figure 2]); 244 observations have both WRB principal qualifier and SOC* content data. The influence of the soil WRB principal qualifier on SOC* content is shown in Figure 7.

The most frequently recovered WRB principal qualifier linked with SOC* is, by far, 'Spolic' (167 observations), which characterizes the presence of more than 35% (by volume) of industrial waste among the artefacts present in the Technosols. Spolic Technosols are mainly related to industrial land uses (57% of observations). SOC* content in Spolic Technosols is $3.7 \pm 5.7\%$; it is close to SOC* mean and standard deviation of the entire dataset.

The second most frequently recovered WRB principal qualifier is 'Urbic' (29 observations), which characterizes the urban origin of artefacts that are mainly composed of rubble and refuse of human settlements (more than 35% by volume). Consistently, all the Urbic Technosols are related to urban land uses. SOC* content in Urbic Technosols is $2.6 \pm 2.4\%$; it is less than the Spolic Technosols mean and also less widely spread. Maximum SOC* content of Urbic Technosols is lower than that of Spolic Technosols: 8.8% against 38.8%, respectively.

The third most frequently recovered WRB principal qualifier is 'Linic', with 14 observations; it describes soils with a continuous, very slowly permeable to impermeable constructed geomembrane. SOC* content in Linic Technosols is $4.0 \pm 1.7\%$. These 14 observations concern soils of waste material deposits from a former petroleum refinery where a geomembrane has been observed (Heidari & Asadi, 2015).

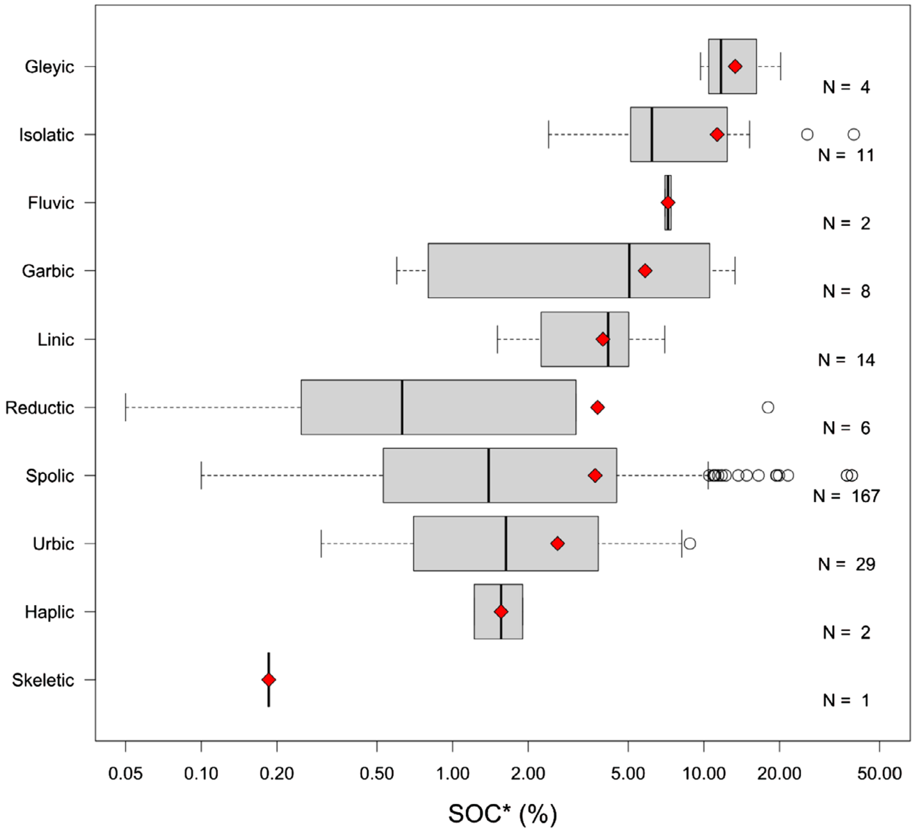

FIGURE 7 Link between WRB principal qualifier and SOC* content in Technosols. Logarithmic scale is used in the boxplot for a better visualization of low value data. WRB, World Reference Base for Soil Resources [Color figure can be viewed at wileyonlinelibrary.com]

Isolatic Technosols (SOC* = 11.3 ± 11.5%, 11 observations) concern 'soils having, above technic hard material or geomembrane, soil material containing fine earth without any contact to other soil material'. Garbic Technosols (SOC* = 5.8 ± 5.6%, eight observations) are soils where artefacts are mainly composed of organic wastes. Skeletic (0.18%), Reductic (3.8 ± 7.1%), Haplic (1.6 ± 0.5%), Gleyic (13.3 ± 4.7%) and Fluvic (7.2 ± 0.3%) are WRB principal qualifiers that are here rarely used for the description of Technosols (15 data over the 244 data in Figure 7), which is consistent with the fact that they are more related to natural soils.

4 | DISCUSSION

4.1 | How to study carbon stocks in soils with a strong human influence?

As shown previously (section 3.1), the publications that are used in this study contain the word 'Technosol' in the research equation. They represent only a fraction (2%) of all the publications whose theme is related to 'organic carbon' and 'soils with strong human influence' (i.e., urban, industrial and mining soils). The term 'Technosol' (or its plural form), although quite specific, is preferred to the more general ones, because it relates to a specific type of soil, the target of this work. Its usage also implies that the studied soils meet technical criteria, usually established by soil scientists with an adequate pedological approach that is specifically looked for in our study (e.g., division and description of the soil according to soil horizons). A representative selection of the publications obtained by Equations (2) to (4) has been read, but the information required to classify the studied soils as Technosols is frequently lacking. The integration of such data would have weakened the present work, which aims to complete the global soil carbon budget by filling in the gaps of Technosols' contribution. Eventually, the research equation leads to an acceptable number of articles to be exploited for data extraction. A potential limitation of our approach is the fact that the Soil Taxonomy does not use the same terms and prefers the categories 'human-altered and human-transported (HAHT)' (Levin et al., 2017), limiting the number of soils with a strong human influence in North America. Only a few Technosols are recorded under tropical and polar climates (eight and four observations respectively), also limiting the representativeness of our database for these conditions.

When SOC data were missing, SOM data were converted by default to SOC by multiplying by 0.58. This conversion factor has been widely used in less anthropized soils but might not be adequate for all the various situations encountered in Technosols. Indeed, depending on organic matter types, this factor has been shown to vary from 1.4 to 2.5 (Pribyl, 2010). Currently, there is no publication reporting large datasets with SOC to SOM ratios for Technosols. Asabere, Zeppenfeld, Nketia, and Sauer (2018) found an SOC to SOM ratio of 2.7 in fine earth for a limited number of urban soils. In our meta-analysis dataset, the mean ratio of SOC to SOM for Technosols was 2.30 ± 2.41, but limited to 20 observations due to the scarcity of the coexistence of both parameters. Further research is therefore needed to explore the diversity of organic matter in Technosols. Considering all these aspects, our hypothesis regarding converting SOM to SOC may have led to slight overestimations of carbon stocks in Technosols but does not change the overall trend of this work.

One crucial aspect of the evaluation of carbon stocks in soils has always been the consideration of the contribution of coarse fractions (Corti et al., 2002; Poeplau et al., 2017). This point is of great interest as the Technosols are well known to contain high quantities of coarse fractions from various origins (Allory et al., 2019; Rokia et al., 2014; Watteau et al., 2018). This is also of interest when considering that, in contrast to most of the natural soils, such coarse artefacts are also organic in Technosols (e.g., charcoal, wooden boards, garbage and bitumen) and could increase their actual stocks of carbon.

Overall, it appears that our scope is traditionally, as in all meta-analysis about carbon in soil, limited by the availability of joint data on both SOC, depth and bulk density. As a consequence, we would contribute to the discussion by emphasizing the necessity to acquire robust full data to achieve such a crucial objective as evaluating carbon storage in all soils.

4.2 | How organic carbon stocks of Technosols are ranked compared to natural soils

Overall, and despite a strong variability that will be addressed below, it appears that Technosols have, on average, high SOC contents compared to natural and less anthropized soils. The strongest differences are particularly observed at surface and deep horizons. The SOC content of Technosols (9.1 ± 12%) in top layers is lower than the highest SOC contents found in natural soils such as Histosols (between 45 and 20% for the topsoil; Vepraskas & Craft, 2015) and Podzols (between 25 and 5% for the topsoil; Jones, Hiederer, Rusco, & Montanarella, 2005). However, Technosols still account for high SOC contents compared to the more common natural soils such as Cambisols or Luvisols (around 2.5% SOC content in topsoil; Jones et al., 2005).

These differences are strengthened in deeper horizons. Technosols have more than 10 times the SOC content of other soil types in deep horizons (60–100 cm): 3.3% in Technosols against 0.19% to 0.26% in Alisols, Arenosols, Cambisols, Luvisols, Podzols, Fluvisols, Gleysols, Podzoluvisols and Histosols in Denmark. This is also confirmed by comparison with data from deep horizons (60–100 cm) of Albaladejo et al. (2013): 3.3% in Technosols against 0.21% to 0.46% in Calcicol, Regosol, Cambisol, Fluvisol, Kastanozem and Leptosol, for Solonchak in the Murcia province in Spain.

The meta-analysis permits recovery of only a few observations with data available for SOC stock calculation (76 observations). However, this dataset still contributes to a first rough estimation of SOC stocks in Technosols. The mean SOC stock is 73.2 t C ha^{-1} in 0–30 cm; this directly ranks Technosols among the six Reference Soil Groups with the highest carbon stocks per unit area according to the global soil organic carbon map (FAO, 2018). Updated ranking of SOC stocks per type of soil might be: Histosol (132 t C ha^{-1}) > Chernozem (89 t C ha^{-1}) > Gleysol (88 t C ha^{-1}) > Podzol (81 t C ha^{-1}) > Andosol (76 t C ha^{-1}) > Technosol (73 t C ha^{-1}) > Cambisol (63 t C ha^{-1}) > (…).

The inclusion of Technosols in this ranking may seem premature in view of the quantity of data, but it nevertheless highlights the potential that Technosols have in terms of carbon stocks.

Beyond the global interpretation based on the mean values, the standard deviations express a massive heterogeneity of the SOC contents in Technosols. Coefficient of variation of SOC* varies from 104% (in 10–30 cm) to 228% (in 30–60 cm), whereas coefficient of variation is 'only' 45 to 56% for Cambisol, 43 to 68% for Luvisol and 45 to 58% for Stagnosol (A, E and B horizons from Grüneberg, Schöning, Kalko, & Weisser, 2010). Indeed, in Technosols, there are some extremely low values on their surface, with almost no equivalent in natural soils, and very high contents at depth, with few equivalents in natural soils: Histosols, Podzols, Chernozems, Phaeozems, Umbrisols. Such a huge heterogeneity makes it impossible for now to extrapolate or spatialize SOC stock values in Technosols at any scale.

4.3 | What are the factors explaining such a high heterogeneity?

4.3.1 | Depth

There is an overall trend of SOC* decrease with depth in Technosols according to the models. Those that have been applied were initially developed for natural and agricultural soils and are strongly dependent on the SOC content in the 0–10 cm layer (Minasny, Stockmann, Hartemink, & McBratney, 2016). However, the relation between SOC* and depth was shown to be very weak and poorly significant (correlation coefficient = −0.10, $R^2 \approx 0.1$ for both models). Many features of SOC* distribution in Technosols (high variability at all depths, including high content in deep horizons) reveal the necessity to use different models as a function of a typology of Technosols.

In other terms, given the actual state of knowledge, depth is not a major influencing factor in Technosols; high variability of SOC* content is encountered at all depths and must be explained by other factors. This is consistent with the fact that Technosols are often restructured by human activities such as construction, where natural soil materials can be buried at depth, truncated, excavated and deposited after a while, erasing the classical SOC gradient observed in less anthropized soils.

4.3.2 | Artefacts

The nature of artefacts can be assessed through two proxies: land use and WRB principal qualifiers data analysis.

Land use is here considered to have two main impacts on Technosols: (a) distribution and allocation of soil constituents as well as physical properties through the type of human actions on the soils (i.e., dumping, excavation, burying and compaction); and (b) chemical composition, linked to the nature of artefacts introduced by the different land uses. Artefact introduction might be due to either passive or unintentional actions (e.g., industrial activities waste unintentionally deposited on/in soils) or active and intentional approaches that notably aim to reclaim degraded soils (generally by using organic amendment) (Pichtel, Dick, & Sutton, 1994; Séré et al., 2008; Šourková et al., 2005; Vetterlein & Hüttl, 1999).

Due to the limited availability of information on the Technosols' formation and to our methodology for collecting information, it is not possible to analyse the physical contribution of human actions beyond the heterogeneous SOC content depth distribution. On the contrary, the nature of artefacts is easily related to past or present mining, industrial or urban anthropic activities. Many artefacts resulting from industrial activities (wood, charcoal, coal, coked-coal and asphaltic concrete) contain high amounts of organic carbon (Howard, 2017), which are also highly recalcitrant and could thus contribute to high carbon storage (Biache et al., 2013). Organic artefacts may also be introduced in soils by some specific mining and urban activities (e.g., coal or lignite mining activities; Greinert et al., 2018; Hüttl & Weber, 2001; Uzarowicz et al., 2018). As mentioned, restoration or reclamation processes involve the spreading or even massive use of organic amendments such as compost, biochar or sewage sludge that contribute considerably to high SOC stocks in soils of urban, industrial, traffic, mining and military areas (SUITMAs) (Carabassa, Ortiz, & Alcañiz, 2018; Larney & Angers, 2012).

The WRB principal qualifier is the second proxy for the determination of the nature of the artefacts. Three of the five most employed WRB principal qualifiers are related to the nature or origin of artefacts: Spolic (related to industrial activities), Urbic (related to urban activities) and Garbic (mainly related to the use of organic amendment, such as sewage sludge or compost). Based on the description of the WRB, and based on our findings, artefacts corresponding to the 'Garbic' qualifier are necessarily of an organic nature, artefacts corresponding to the 'Spolic' qualifier may be of either mineral or organic nature, and artefacts corresponding to the 'Urbic' qualifier are mainly of a mineral nature (e.g., lime concrete, mortar, lime brick, ceramic brick and drywall; Greinert & Kostecki, 2019). This could explain the obtained ranking of SOC content: Garbic > Spolic > Urbic, qualifiers with artefacts whose nature is systematically organic having logically higher SOC content.

As a result, our strong finding is that land use, mainly through the impact of the nature and origin of the artefacts that are intentionally or unintentionally introduced into soils with a strong human influence, is a major factor in explaining the SOC in Technosols. The WRB principal qualifier is also efficient in explaining SOC of Technosols and the combination of both WRB qualifier and land use may be complementary. On this basis, we would like to strongly encourage our colleagues to go to the effort of giving relevant qualifiers to their studied Technosols.

4.3.3 | Climate and hydrological conditions

Climate shows a significant effect on SOC content from the surface of the studied Technosols (i.e., topsoil [0–30 cm] and upper horizons). SOC content as a function of climate follows the order: dry climate, temperate climate, continental climate. Dry climate areas in the Köppen-Geiger classification correspond to areas where mean annual precipitation is lower than 20 times the mean annual temperature (Peel et al., 2007). Low precipitation and high temperatures are conditions favourable to soil organic matter mineralization and generally result in low SOC content and stocks, which is consistent with our finding (Albaladejo et al., 2013; Liu, Shao, &

Wang, 2011; Minasny, McBratney, Malone, & Wheeler, 2013). Temperate climate areas in the Köppen-Geiger classification are areas where mean temperature of the coldest month is between −3°C and 18°C and it is above 10°C in the hottest month, whereas continental climate areas are areas where the mean temperature of the coldest month is below −3°C (Peel et al., 2007). Colder temperatures are favourable for carbon sequestration; it is thus not a surprise to have such a ranking and significant differences of SOC between Technosols under temperate and continental climates. Such observations have also largely been carried out for natural and less anthropized soils (Doetterl et al., 2015; Gray, Bishop, & Wilson, 2015; Guggenberger et al., 2020). However, the significant difference in SOC content between soils from continental and temperate climates appears surprising considering that the studied Technosols are very young (median age of Technosols is 6 years, $N = 518$ observations). Further research would be required to highlight the kinetics of OM transformation in Technosols, especially under dry climatic conditions, to demonstrate the importance of early pedogenesis.

The impact of hydrological conditions on the organic carbon cycle operates in partial relation to the climate. In natural soils, these are notably expressed by such qualifiers as 'Gleyic' and 'Reductic'. In Technosols, additional qualifiers are used such as 'Linic', which describes the in-depth 'presence of a slowly permeable to impermeable constructed geomembrane' or 'Isolatic', which describes a soil '…/… above technic hard material, above a geomembrane…/…', which in our cases expresses urban shallow soils over buildings and walls (Bouzouidja et al., 2018; IUSS Working Group WRB, 2014; Markiewicz et al., 2018). The presence of a continuous impermeable layer logically leads to a limitation of water flow that contributes to reductic conditions inducing limited biological activity and limited organic carbon mineralization. As a consequence, the limited number of Technosols with these qualifiers exhibit high SOC* as well (green roofs are also designed with a high concentration of SOC to meet the high requirement of physicochemical fertility). Such findings underline the crucial importance of a pedological approach to describe soil profiles, particularly in Technosols.

4.3.4 | Nature and presence of vegetation

Surprisingly, no significant effect of soil cover, that is, vegetation, is highlighted. Conversely, Xiong et al. (2014) observe a significant effect of land use and soil cover changes, and combined land use and soil cover change and climate effect, but no significant effect of climate alone on SOC changes. Again, our assumption is that most of the studied Technosols are too young to exhibit a visible influence of vegetation on their SOC.

5 | CONCLUSIONS

Soil organic carbon content in Technosols is very high compared to less anthropized soils. These differences are even more marked in deeper horizons. However, this high SOC content is systematically coupled with high variability. Our results contribute by demonstrating the truly original features of Technosols, compared to all other natural and agricultural soils. If some of the controlling factors highlighted in this study are to some extent common (e.g., influence of climate), others are more original.

This study underlines the importance of the notion of artefacts in Technosols. The origin and nature of artefacts seem to play a major role in the carbon cycle. Organic artefacts can either be introduced voluntarily into the soils, mostly for reclamation purposes (e.g., organic amendments and biochar), or unintentionally (e.g., charcoal, lignite and coked-coal) by human activities. The presence of organic artefacts means that SOC in Technosols can be either anthropogenic or of natural origin. The major conclusions of our work are to focus attention on the evolution and interactions of anthropogenic and non-anthropogenic organic matter in Technosols' pedogenesis. In addition, mineral artefacts are also expected to contribute to carbon dynamics.

Given the continued spread of anthropized areas, there is a strong need to take Technosols into account in global soil carbon budgets. Considering the high reactivity of artefacts, their potential for carbon sequestration is at the present time hard to assess but also strongly promising.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Victor Allory: Conceptualization; data curation; formal analysis; methodology; writing - original draft. **Geoffroy**

Séré: Conceptualization; methodology; supervision; writing-review & editing. **Stéphanie Ouvrard:** Conceptualization; methodology; supervision; writing-review & editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ORDAR at https://doi.org/10.24396/ORDAR-60, reference number ORDAR-60.

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