Passive CO₂ removal in urban soils: Evidence from brownfield sites

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HIGHLIGHTS

- Soil carbonate in urban brownfield lands contribute to significant removal of CO₂.
- Study of 20 brownfield lands show removal rate of 4–59 t CO₂ ha⁻¹ yr⁻¹.
- CO₂ sequestration rate is highest in the first 15 years after demolition.
- Sites that sequestered CO₂ possess a similar risk of flooding to sandy soils.
- Substrate strength, measured in-situ, increased with carbonation

ABSTRACT

Management of urban brownfield land can contribute to significant removal of atmospheric CO₂ through the development of soil carbonate minerals. However, the potential magnitude and stability of this carbon sink is poorly quantified as previous studies address a limited range of conditions and short durations. Furthermore, the suitability of carbonate-sequestering soils for construction has not been investigated. To address these issues we measured total inorganic carbon, permeability and ground strength in the top 20 cm of soil at 20 brownfield sites in northern England, between 2015 and 2017. Across all sites accumulation occurred at a rate of 1–16 t C ha⁻¹ yr⁻¹, as calcite (CaCO₃), corresponding to removal of approximately 4–59 t CO₂ ha⁻¹ yr⁻¹, with the highest rate in the first 15 years after demolition. C and O stable isotope analysis of calcite confirms the atmospheric origin of the measured inorganic carbon. Statistical modelling found that pH and the content of fine materials (combined silt and clay content) were the best predictors of the total inorganic carbon content of the samples. Measurement of permeability shows that sites with carbonated soils possess a similar risk of run-off or flooding to sandy soils. Soil strength, measured as in-situ bearing capacity, increased with carbonation. These results demonstrate that the management of urban brownfield land to retain fine material derived from concrete crushing on site following demolition will promote calcite precipitation in soils, and so offers an additional CO₂ removal mechanism, with no detrimental effect on drainage and possible improvements in strength. Given the large area of brownfield land that is available for development, the contribution of this process to CO₂ removal by urban soils needs to be recognised in CO₂ mitigation policies.

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1. Introduction

In the context of climate change and population growth, urbanisation presents both challenges and opportunities (Seto and Shepherd, 2009). The proportion of the global population living in cities increased from 34% (1960) to 54% (2015) and is projected to reach 66% by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2015). Urbanisation exerts pressure on the natural environment, but cities also offer opportunities to meet global sustainable development goals as they can act as hubs for climate change adaptation and social innovation strategies (Grimm et al., 2008; McPhearson et al., 2015; United Nations, Resolution adopted by the General Assembly on 25 September 2015, 2015). One area for such innovation is in the management of urban ecosystem services, which improve the well-being of urban citizens (Bolund and Hunhammar, 1992; Perring et al., 2012; McPhearson et al., 2015). Urban lands play an essential role in delivering these ecosystem services and in minimising the negative impacts of urbanisation (Pavão-Zuckerman, 2012). In established urban areas, the term 'brownfield' is used for land that has previously been developed, usually for industrial or commercial purposes. Where development takes place on natural or agricultural fields, or substrates, are spatially heterogeneous and diverse, reflecting often complex site histories that in industrialised regions can involve multiple phases of demolition and construction spanning 200 years or more. The texture of such soils and the size and connectivity of their pore space may vary greatly, and at a range of scales. Observation of samples from trial pits indicates that calcite precipitation takes place in urban brownfield lands include fine grained demolition materials left behind by the on-site crushing and screening of concrete (Renforth et al., 2009; Washbourne et al., 2012, 2015; Manning and Renforth, 2013; Jorat et al., 2015). These materials contain the calcium-rich components of cement (portlandite, Ca(OH)$_2$, and artificial calcium silicates) and plaster (gypsum, CaSO$_4$.2H$_2$O). Calcium may also be derived from the weathering of natural silicate rocks such as dolerite (Manning et al., 2013), which may be used as construction aggregates or substrates, are spatially heterogeneous and diverse, reflecting often complex site histories that in industrialised regions can involve multiple phases of demolition and construction spanning 200 years or more. The texture of such soils and the size and connectivity of their pore space may vary greatly, and at a range of scales. Observation of samples from trial pits indicates that calcite precipitates onto grain surfaces and so reduces pore volume (Fig. 1). While pore space may be essential for providing a solution flow to supply the calcium and carbonate required for calcite precipitation, this porosity is diminished as carbonation proceeds, and may affect drainage in fine-grained components of the soil.

The observation that calcite precipitation takes place in urban brownfield lands provides an opportunity to adapt their management
to promote carbonation and augment other practices which aim to remove atmospheric CO₂. A key factor is the availability of calcium, which needs to be present in sufficient quantity to enable calcite precipitation to take place. Thus, the first step in land management for this purpose is to promote soil calcium availability, such as by retention on site of fines produced by crushing concrete during demolition. An inevitable consequence of urban development, demolition is often followed by a delay before new construction, during which time the land may have a formal or informal temporary use as a green space, thus enabling photosynthetic carbon to enter the soil. Although individual sites will have specific soil characteristics, an open texture as shown in Fig. 1 is unlikely to be preserved following later construction. Nevertheless, once formed, soil carbonate minerals are stable, and do not release C back into the atmosphere. C captured in this way will remain in the solid during reworking associated with later development. Active management of brownfield sites to increase their potential for CO₂ removal (Louwagie et al., 2016) also promotes other ecosystem services (Haase et al., 2014). These principles need to be understood in the context of cities in developed, but also developing, countries where urban spread into former agricultural land will increase the rate of brownfield creation in 20–50 years, as current buildings come to their end of life.

To fully understand the future importance of calcite precipitation and its associated impacts for CO₂ removal in urban brownfield land, several questions need to be addressed.

First, it should be established whether reported carbonation rates are typical of those in brownfield soils, and by how much rates vary. Carbonation has been assessed on a small number of sites to date, where rates may not be typical.

Secondly, the duration of calcite precipitation needs to be determined, to establish whether or not the process stops after a specific period. Previous estimates of annual rates of CO₂ sequestration in brownfield sites (e.g., Renforth et al., 2009; Washbourne et al., 2012) are based on assumed intervals between demolition and soil analysis. In principle, as long as vegetation is growing, calcite precipitation will stop when either the soil calcium is exhausted, or when the pore space in which CaCO₃ forms is filled.

Thirdly, given that brownfield sites are heterogeneous in their soil properties and vegetation, then it is important to understand how variation in these properties relates to inorganic carbon formation. pH is a fundamental control on carbonate mineral stability. Carbonate minerals typically form in soils with pH >7.3 (Lal, 2008), and have been found to precipitate in sanitary landfills at pH as low as 5.9 (Manning and Robinson, 1999); brownfield soils can display high pH (9.5–11.7 of Washbourne et al., 2015). Electrical conductivity reflects the soil solution solute content; for example, if gypsum is present, electrical conductivity will be relatively high. Brownfield sites also vary in the extent of vegetation cover, partly depending on the time available since demolition for plant succession to occur. Plants could play a major role in the input of carbon into the soil system by releasing CO₂ into the soil via root respiration and also through the deposition of leaf and root litter, and organic acids as root exudates, all of which are decomposed to release CO₂ into the rhizosphere. By reducing uncertainty in the rates of carbonation that can be expected, and by identifying soil factors which predict carbonation rates, carbonation through drainage will be reduced, potentially leading to increased flooding in urban areas during heavy rainfall. In terms of soil mechanics, calcite precipitation can increase strength by up to 70% in experimental situations (Bertos et al., 2004). Indeed, the artificial use of Microbial Induced Calcite Precipitation (MICP) has been considered for ground improvement as it enhances strength and reduces permeability (e.g., Dejong et al., 2006; Al Qabany and Soga, 2013). All of these properties influence the capacity for carbonate-forming soils to be built upon – a likely necessity in the management of brownfield lands.

To better understand how the aforementioned factors influence rates of calcite precipitation in soil and the effect of this CO₂ removal process on soil physical properties, we collected data relating to the accumulation of calcite, soil and vegetation properties and also changes in soil structure that affect the permeability and bearing capacity of urban soils in 20 brownfield sites in north-east England. This paper expands considerably upon previous work on urban brownfield land carbonation at a single site (Washbourne et al., 2015) by studying a wider range of brownfield sites. We use statistical analysis to assess whether or not there are general predictors of carbonation rates, and to assess the relationship between carbonation and properties which may affect future building developments. The overall goal is to support decision making in urban land management that seeks to maximise CO₂ removal, while retaining other benefits (Louwagie et al., 2016).

2. Methods

In 2015, four brownfield sites in Newcastle, in 2016, 20 brownfield sites across Newcastle, Gateshead, North Shields, South Shields, Stockton-on-Tees and Hartlepool and in 2017, three brownfield sites in Newcastle were visited (Table 1). Permanent markers and mobile GPS equipment were used to ensure the accuracy of sampling in sites where repeat visits were made. Sample collection was similar to the approach used by Rawlins et al. (2008), who collected 0.5–1.0 kg to a depth of 15 cm, and by Washbourne et al. (2015) who collected 0.5–1.0 kg to 10 cm depth. In this study, a 0.5–2.5 kg soil sample to the depth of approximately 20 cm was collected from each of 10 sampling locations; samples were not pooled. Sampling locations were selected to maximise variability across gradients of soil type and vegetation and were a minimum of 20 m apart from each other. In-situ California Bearing Ratio (CBR) tests were conducted prior to the soil sampling. The collected soils consisted of demolition rubble containing fragments of building materials grading from clay-sized particles to large brick/concrete pieces of up to 5 cm.

After sampling, soils were weighed using a portable balance with the accuracy of ±5 g and stored inside a sealed plastic bag. Dry sand with known bulk density was used to fill the hole where the soil was collected. The accurate weight of the sand used to fill the hole was measured in the field. Considering the weight of the dry sand used to fill the hole and the sand’s bulk density, the volume and hence bulk density of the collected soil sample can be calculated. In the laboratory, samples were air-dried, disaggregated by hand using a pestle and mortar, and sieved. For consistency, the ~250 μm fraction was analysed by I2 Analytical Ltd. (Watford, UK) to determine inorganic carbon by acid digestion following BS 1377–3: 1990, and reported as equivalent calcium carbonate. This method provides a direct and unambiguous determination of carbonate carbon. Total inorganic carbon (TIC) and CO₂ equivalences were calculated stoichiometrically. Electrical conductivity was measured using a Hanna HI 9835 Conductivity/TDS meter, pre-calibrated using electrical conductivity calibration solution (0.010 mol/L) potassium chloride.

Ratios of stable isotopes of C and O, expressed relative to Vienna Pee Dee Belemnite (VPDB), were determined for 73 of the soil samples collected in 2016 and 8 Carboniferous Limestone samples by Iso-Analytical (Cheshire, U.K.) using a Europa Scientific 20–20 continuous-flow
isotope ratio mass spectrometer (IRMS). Four samples were submitted for each site, except for Site H for which only three were selected (79 in total; 6 analyses failed to provide isotope data), based on a range of sample TIC values. For these samples, the same material was used to determine both inorganic carbon and the C and O isotope ratios.

In-situ CBR values were obtained using a hand-driven British Military Engineering Experimental Establishment (MEXE) Cone Penetrometer. The penetrometer is pushed into the top 150 mm of soil and the in-situ CBR value of in-situ CBR recorded (Cook et al., 2016). Three in-situ CBR readings were taken at each sampling location prior to sampling. The instrument displays the in-situ CBR immediately as the probe is being manually forced down into the ground. As this instrument is heavily dependent on the strength of the operator, tests were completed by the same person. The MEXE Probe cone penetrometer is designed specifically for fine-grained soils, and penetration was challenging when encountering hard demolition waste such as bricks and rock or masonry.

Due to the heterogeneous nature of the brownfield sites, remoulding the collected soil samples in the laboratory to represent the in-situ condition for the conventional permeability analysis (e.g., falling head or constant head permeability tests) is accompanied by a significant level of error and ultimately results in inaccurate measurement of soil permeability. As measurement of the in-situ permeability was not logistically possible, an updated version of Hazen’s formula was used to estimate the hydraulic conductivity of each sample. Chapuis (2004) proposed the modified Hazen’s formula as shown in Eq. (1) to calculate permeability as this formula relates the function of particle size and void ratio in coarse-grained soils:

\[ K = 2.4622 \times \left( \frac{D_{10} \times e^1}{(1 + e^1)^{0.7825}} \right) \]

where \( e = \) void ratio and \( D_{10} = \) effective particle size acquired from particle size distribution curve.

Paired t-tests were used to determine whether there were significant changes in TIC content over time in sampled in consecutive years. In order to better understand the variation in carbonate precipitation within and between brownfield sites, the amount of TIC was modelled using mixed-effects statistical models according to a model selection procedure (Pinheiro and Bates, 2000). TIC and silt+clay content were log transformed to account for non-normality in variance, and an outlier data point with extremely low pH (3.5) was removed.

Our model selection approach involved adding explanatory variables in fixed sequential order according to a hypothesized ‘hierarchy of controls’ which impact the basic processes of plant growth and organic matter (OM) decomposition and stabilization (Diaz et al., 2007; Manning et al., 2015). First, we added site age, and this was followed by the physical and chemical properties of soil that are driven mainly by site history and/or underlying parent material (soil pH, electrical conductivity, silt and clay content). Finally, we added plant cover. Variables were retained if they improved model likelihood, assessed using Akaike’s Information Criterion corrected for small sample sizes (AICc), and were significant (at \( p < 0.05 \)), assessed using likelihood ratio deletion tests (LRT). At each stage, first order interactions between significant variables were sought, as were quadratic relationships, if there was a hypothetical basis for them. At the end of each stage of model selection, interactions between newly retained variables and those retained from previous steps were sought and retained if significant. Once the final model was reached each term was removed from the model and its significance was assessed using a LRT. The modelling process indicated a negative effect of plant cover but this variable was removed from the final model as there was no hypothetical basis for a mechanistic relationship that was negative (see introduction).

To estimate the variance explained by the fixed effects of the models, we used the r.squaredGLMM function of the MuMIn package which partitions the explained variance by comparing the fit of model predictions to the data when these terms are absent from the model to calculate a ‘marginal R2’ (R2M). The importance of each variable in the model was also estimated by observing the AICc change (\( \Delta AICc \)) on deletion (Nakagawa and Schielzeth, 2013). All models were linear mixed-effects models with a random effect for site. Mixed models were fitted using maximum likelihood and the lmer function of the statistical software R version 3.4.1 (R Core Team 2017).

### 3. Results

TIC varied considerably across the sites, with mean TIC content per site ranging from 0.76–4.87% dry weight. pH varied from 7.1–8.8, silt+clay from 0.71–5.6%, electrical conductivity from 155–787 \( \mu S \) cm\(^{-1}\) and plant cover from 5–93% (Table S1).

The TIC content for brownfield sites visited in 2016 is shown (Fig. 2) relative to site age, and grouped at 5-year intervals (no sites occupied the interval 21–25 years). Site age refers to the time between demolition and our sampling dates. Demolition date was estimated using
historic maps for older sites and taken from site investigation reports for newer sites. For sites younger than 15 years, median TIC values are similar at 2.2%; less than half of this was observed in sites older than 16 years. There was no significant change in soil TIC content between 2015 and 2016 across four sites that were repeatedly sampled and ranged in age between 7 and 26 years (paired t-test, \( t = 1.375, \text{df} = 39, p = 0.177 \)). There was a significant increase in TIC for three younger sites (2–8 years since creation) between 2016 and 2017 (paired t-test, \( t = -7.1659, \text{df} = 29, p < 0.001 \)) (Fig. 3).

The mixed-effects statistical model used to explore relationships between TIC and other soil properties accounted for 47.9% of variation in TIC (R\(^2\)M = 28.1%). Log TIC was best described by a quadratic relationship with soil pH (Table 2), with TIC increasing at a decelerating rate with increasing pH over the observed range of soil pH 5.64–9.49, and peaking at a pH of 10 (Table S1). Variation in TIC was also related to the silt and clay fraction, with amounts being greatest in soil rich in silt and clay sized particles (Table 2). Site age and soil electrical conductivity were not found to be important predictors, while a negative effect of plant cover was found. This variable was removed from the final model as there was no hypothetical basis for a negative relationship.

Carbon and oxygen isotope data for the brownfield sites sampled in 2016 are shown in Fig. 4. For comparative purposes, data are included for local carbonate rocks used in construction (Carboniferous limestone and Permian carbonates, mainly dolomite; Harwood and Coleman, 1981), pedogenic carbonates from natural soils (Salomons et al., 1978; Salomons and Mook, 1976), and calcite associated with concrete structures (Macleod et al., 1991; Krishnamurthy et al., 2003) and steel slags (Renforth et al., 2009). The data for the brownfield sites clearly show overlap with those typical for pedogenic carbonates, with evidence of mixing with geological carbonate (locally derived Carboniferous limestone or Permian dolomite; note that the two Permian samples plotting with the array of pedogenic and brownfield samples are, according to Harwood and Coleman (1981) young pedogenic calcite within Permian dolomite rocks) and with carbonates associated with the chemical weathering of high pH cementitious materials. The array of data for the brownfield sites is similar in range to that reported by Washbourne et al. (2015).

Permeability varied across the sites from 0.0001–0.0502 cm s\(^{-1}\), with most values within the range typical for sand (Fig. 5), and mean values per site ranged from 0.002 to 0.0243 cm s\(^{-1}\) (Table S2). Soils containing 0–4% TIC had 2.5 x higher permeability than those with 4–12% TIC.

In-situ soil strength, as measured as CBR, varied across the sites from 1 to 14 (Fig. 6), with mean values per site ranging from 7.70–12.86% (Table S2). In-situ CBR values were lowest in soils with low TIC content, and greatest for those with TIC >4%. These CBR values are largely within the range of typical sand in-situ (Highways England, 2009).

4. Discussion

Our investigation of 20 sites has shown that calcite commonly occurs in brownfield soils of north-east England: carbon and oxygen isotope
Typical permeability values are those of Lewis et al. (2006). Number of samples = 182. Number of samples = 182. Number of samples = 182.

...nique to atmosphere through a combination of biological processes (photosynthesis) and chemical processes (carbonation at high pH), with mixing of multiple sources to give a composite sample for analysis that also includes varying amounts of limestone derived from construction aggregates. Given that the stable isotope evidence demonstrates the formation of carbonates within the soils from the brownfield sites, in principle we can estimate the rate of their accumulation from repeated sampling, or from the age of the site. Previous attempts to estimate the accumulation rate based on site age (12 years) estimated TIC increases of 25 ± 12.8 t ha⁻¹ yr⁻¹, to a depth of 300 cm, with most carbonate being found at a depth of <100 cm (Renforth et al., 2009). Washbourne et al. (2015) report an accumulation rate of 23 t C ha⁻¹ yr⁻¹, for samples taken to 10 cm depth at an interval of 18 months (i.e. 36–54 months after site establishment). Based on site age and assuming zero inorganic carbon at the time of demolition, our data (for samples to 20 cm depth) for the 20 brownfield sites correspond to an accumulation of TIC of 16 t C ha⁻¹ yr⁻¹, which is comparable to rates estimated by Washbourne et al. (2015), given the difference in the depth of sampling.

At the sites selected for direct measurement of annual accumulation through repeated sampling, rates (Fig. 3a) appear to be very low for sites 10 years or more since establishment, while the more recent sites in this set showed measurable increases over 12 months (Fig. 3b). Accumulation at the most recent site varied from year to year: Site L, 7 years old in 2016, showed little change between 2015 and 2016, but a measurable increase in TIC between 2016 and 2017. The observed variation for sites of different ages suggests that C did not always accumulate at the same rate either between years at the same site, or across the chronosequence. The reasons for this may include (1) mechanical migration deeper in the profile (maximum carbonate occurs in the upper 1 m of soil; Washbourne et al., 2015), or (2) older sites, for which the history is less well known, may have been less suitable for C formation than the younger ones sampled, in some unmeasured property. Interestingly, the difference in carbonate contents of sites older than 15 years (Fig. 2) may reflect introduction of the UK’s Landfill Tax in 1996 and Aggregate Levy in 2002 (Martin and Scott, 2003). This led to increased recycling of construction materials (Tangthithai et al., 2019) and it is possible that the associated widespread use of on-site crushing equipment may have led to more fine-grained crushed concrete entering the soils present at a site.

Statistical modelling considered how pH, silt+clay content and electrical conductivity and plant cover are related to TIC content. These properties were assessed as predictors of carbonate concentrations, together with site age. As might be expected on geochemical grounds, pH was found to describe variation in TIC most closely, with higher content in more alkaline soils. To a lesser extent, TIC was predicted by the

### Table 2
Selected best model for log TIC (wt%)².

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter estimate</th>
<th>AICc</th>
<th>change (ΔI)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-4.472</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>soil pH</td>
<td>1.001</td>
<td>50.26</td>
<td>-0.0001</td>
<td></td>
</tr>
<tr>
<td>(soil pH)²</td>
<td>-0.050</td>
<td>2.38</td>
<td>0.0335</td>
<td></td>
</tr>
<tr>
<td>Log (Silt+Clay)</td>
<td>0.228</td>
<td>7.79</td>
<td>0.0016</td>
<td></td>
</tr>
</tbody>
</table>

a The model was fitted to transformed data so output should be exponentiated if the model is to be used.
b AICc is Akaike’s Information Criterion corrected for small sample sizes.
c Assessed with a single d.f. likelihood ratio deletion test.

Fig. 4. Stable isotope data for samples from brownfield sites collected in 2016, with data for calcite from a range of surface environments (see text for sources). Number of samples from brownfield sites = 79.

Selected best model for log TIC (wt%)².

Fig. 5. Permeability of the samples collected from 2016 versus their CaCO₃ content. Standard error for permeability is 0.007 cm s⁻¹ and TIC is 0.12%, approximately the size of the symbol in the plot. Typical permeability values are those of Lewis et al. (2006). Number of samples = 182.
content of fine material (combined silt and clay content), suggesting that calcite precipitation is greatest in fine-grained soils. This is likely to be due to their greater surface area for reaction. Although TIC accumulation was measurable in younger sites, neither electrical conductivity nor site age were found to be significant predictors of TIC content in the model. Electrical conductivity may be highly variable within a soil of this type, depending on the presence of relatively soluble components such as gypsum or portlandite. The observed high variability may simply reflect very local (within sample) and within-site variability (between the 10 samples) heterogeneity in mineralogical composition (Table S1). Plant cover was negatively related to soil TIC, possibly reflecting a relationship with an unmeasured driver of TIC that also affects plant growth and survival, such as high pH. While the negative relationship between pH and plant cover at the sampling plot scale, which do not show the clear trend with age reported by Washbourne et al. (2015), and accumulation rates are likely to have been underestimated. Accurate determination of soil carbonation in brownfield sites could be achieved by routinely including TIC as a determinant in the suite of elements sought by commercial laboratories in ground investigations that involve trial pits or similar intrusive sampling.

Our results indicate that the retention of crushed demolition waste on site, and/or the addition of new crushed material to sites (e.g., incorporating demolition waste or crushed basic rocks within the landscaping of new urban infrastructure developments), may strongly promote carbon capture. To place this in the context of CO₂ removal on a larger scale, relevant to national targets, and based on an accumulation rate of 16 t C ha⁻¹ yr⁻¹, management of 50,000 ha of urban soils to 20 cm depth has the potential to remove 3 Mt CO₂ yr⁻¹ from the atmosphere, simply as a consequence of carbonation of concrete generated by on-site demolition. The UK has a target to reduce its greenhouse gas emissions from 379 Mt CO₂e in 2016 (Department for Business, Energy, and Industrial Strategy, 2016) to 159 Mt CO₂e in 2050 (Fankhauser et al., 2009). With 400,000 ha urban land (including connecting infrastructure), and 1,365,500 ha suburban land (Rowland et al., 2017), we estimate that management of 1% of this total stock (i.e. 17,655 ha), by providing a source of calcium in the form of crushed concrete or other sources, would remove 1 Mt CO₂ annually. Our results suggest that the process would continue for up to 15 years (Fig. 2), potentially giving a total of 15 Mt CO₂ removal, much of which is removed to deeper in the soil profile, thus accounting for the high TIC values observed in historical sites for the top metre (Renforth et al., 2009; Washbourne et al., 2015). Thus, appropriate management of just 10% of the UK’s urban/suburban land stock could meet 5% of the required
reduction in CO₂ emissions. Similarly, Western Europe has 13 M ha of urban land, increasing at a rate of 4.5% yr⁻¹ (Romano and Zullo, 2013). Managing the area of growth alone (initially 600,000 ha), e.g., by adding crushed concrete or other calcium silicates prior to construction, has the potential to remove ~35 Mt CO₂ annually. This is 12% of the anticipated CO₂ emission target in 2050 recommended by Meyer-Ohlendorf et al. (2018). Beyond Europe, the USA has around 28 million ha urban land (www.census.gov), again offering abundant scope for CO₂ removal through appropriate land management.

5. Conclusions

This study of 20 urban brownfield sites has shown unambiguously, based on C and O isotope analysis, that carbonate minerals have formed as a consequence of reaction between the soil and atmospheric CO₂. The rate of carbonate mineral accumulation corresponds to an increase in inorganic carbon in the top 20 cm of the soil of 16 t C ha⁻¹ yr⁻¹, similar to rates observed in other studies. However, the observed rates varied greatly, and in some case could not be determined in repeated sampling. We conclude that this relates to our experimental design, which does not account for migration of carbonate minerals to greater depths in the soil profile. Although the data show considerable scatter, we find no evidence that soil carbonation reduces permeability to increase the risk of flooding, and overall we observed an increase in soil bearing capacity with increased carbonation.

Declaration of competing 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.

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