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Soil carbon sequestration in building life cycle assessment: Offsetting measure or site impact

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Abstract. The environmental impacts of the built environment typically focus on the materials and operations within the building envelope. Little, if any, consideration is given to impacts that occur outside the building. This can be an appropriate simplification for urban settings where the building dominants the site. However, it would ignore impacts and benefits associated with site activities in more rural settings. The present study investigates soil carbon sequestration (SCS) principles to determine whether SCS can be considered an offsetting measure for buildings or should be considered within the site impacts for a project. Soil organic carbon (SOC) levels change overtime in response to external factors and interventions, however this response time is within the reference study period commonly used for building-scale life cycle assessments (LCAs). Therefore, it would be plausible to monitor changes in SOC throughout the lifespan for a project. Currently, there are some emerging methods but no consensus standards on accounting for SCS in building LCAs and current methodologies for quantifying SCS need further development to align with carbon offset principles. However, since soil is an intrinsic part of the landscape, it would be appropriate to incorporate SCS within the use phase impacts for a site. Expanding the system boundary to account for SCS should include accounting for the environmental impacts associated with landscaping, maintenance, and land management practices. Guidelines for calculating SCS and landscaping environmental impacts need to be developed to better reflect the complete environmental impact of the built environment.

1. Introduction

The built environment is seeking ways to reduce its environmental impacts to meet impact reduction targets and mitigate the worst impacts associated with climate change. The built environment contributes 37% of global anthropogenic greenhouse gas (GHG) emissions [1]. Life cycle assessment (LCA) is being used to quantify the environmental impacts of buildings. However, the assessment scope is predominantly limited to the materials, activities and consumption of energy that occur within the system boundary defined by the building footprint and envelope [2]. More specifically, building LCAs have predominantly focused on the operational energy use impacts and the upfront embodied impacts associated with the substructure, superstructure and enclosure [3]. More recent efforts are considering the environmental impacts associated with mechanical, electrical, and plumbing (MEP) systems and interiors. Limited work has been undertaken to understand and mitigate the environmental impacts of the landscape, and associated site activities, that interconnects our buildings [4].

In efforts to lower environmental impacts and reach some form of net-zero classification, the built environment is exploring: carbon sequestering and biogenic materials, the overproduction of renewable energy, carbon offsets, and the reuse of materials, among other reduction strategies. Even though soil carbon represents the second largest carbon pool globally [5], few studies have considered how the landscapes within our built environment can act as a carbon sink. Unfortunately, increases in global temperature will potentially have adverse effects on soil carbon levels [6, 7]. Additionally, site activities can influence the carbon flows between the soil, biogenic matter and the atmosphere further influencing soil carbon levels. Broadening the system boundary to encompass the entire site for a project would provide a more holistic view of the environmental impacts associated with the built environment. Unfortunately to date, there is no consensus standard for how site activities, and more specifically soil carbon sequestration (SCS), should be quantified nor reported within LCAs for the built environment [8].

This paper aims to bridge the gap between the fields of soil carbon, carbon offsets and building LCA to investigate how SCS can be incorporated into LCAs for the built environment. In doing so, this paper explores whether on-site SCS could be considered as a carbon offset or reported as site impacts that correlate to the life cycle stage framework defined by EN 15978 [9]. Therefore, this paper serves to answer the following questions:

1. Does soil carbon sequestration meet the requirements to be considered a carbon offset?
2. How does SCS align with the life cycle stages of a built asset?
3. What LCA methodology should be used to quantify SCS?

The principles behind soil carbon sequestration and carbon offsets are summarized in Section 2. Section 3 describes a case study building used as an example for SCS. Section 4 summarizes the on-site soil carbon levels for the project. Section 5 discusses whether these processes can be incorporated into building LCAs as an offset or as site impacts. Section 6 summarizes the main findings from this study and proposes future work focused around incorporating site impacts into LCA frameworks.

2. Background

2.1. Soil Carbon Mechanics

Soils naturally store carbon due to the presence of organic matter [5]. The amount of carbon stored within soil is influenced by multiple factors that are well documented within agricultural and ecological literature, including: soil properties, climate conditions, and land use patterns [10]. Under consistent conditions, the release of carbon to the atmosphere, through respiration, and the rate of soil carbon sequestration (SCS) exist at a steady-state [10, 11]. However, certain land management practices and interventions can be implemented to encourage greater SCS rates and therefore increase the soil organic carbon (SOC) level to a new steady-state [11]. In addition to the factors influencing SOC, the SCS rates can be influenced by: grazing patterns, fertilizer use, vegetation type, land gradient and maintenance routines, among others [5, 11-14]. Evidence indicates that SCS rates decrease over time as the soil carbon approaches a new steady-state which typically occurs after approximately 20-30 years [11, 12]. SCS is a complex process and SOC can be negatively impacted by disturbing the topsoil which leads to a rapid release of carbon from the soil to the atmosphere [10]. Therefore, decreasing SOC at a much greater rate than SCS rates can recover this lost soil carbon. Eventually, soil will reach a theoretical carbon saturation point that is dictated by its physical properties and climate conditions and once the saturation point is reached the soil will not be able to sequester additional carbon [12]. Figure 1 presents a conceptual visualization of changes in SOC over time.

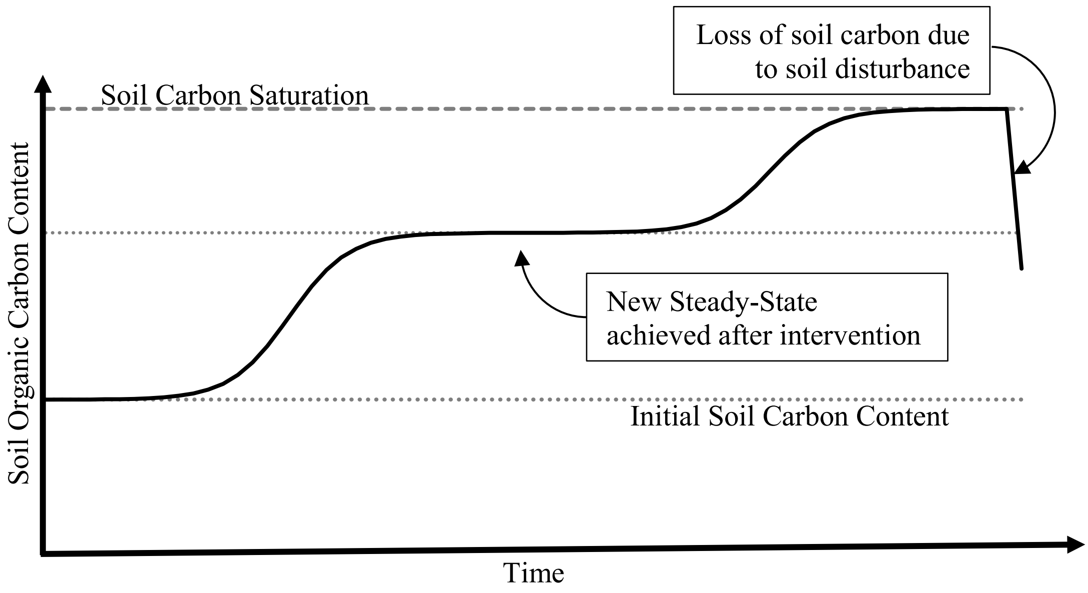

Figure 1. Change in soil carbon over time, based on West & Six [12].

Prior to implementing an intervention, it is important to understand the existing site conditions to understand the degree to which specific interventions can influence the SOC content. Table 1 summarizes common natural processes and interventions that influence SOC content as discussed within literature [7, 13, 15]. Each intervention can be implemented to varying degrees across a site. The magnitude to which a natural process or intervention can influence the SOC is dependent on the local climate, the site conditions, the geological and physical properties of the soil and the interdependencies of the existing conditions and the factors leading to a change in SOC [16].

Table 1: Natural Processes and interventions that can influence SOC [7, 13, 15]

Natural Processes	**Interventions**
Weather Patterns	Grazing Patterns
Extreme Weather Events	Fertilizer Use
Soil Erosion	Crop / Vegetation Rotation
Microbial Organisms	Drainage
Fire	Tillage
	Land Use Change
	Biochar application

2.2. Carbon Offsets within the Built Environment

Carbon offsets have experienced a growing focus as individuals, organizations, industries and governing bodies set impact reduction targets and establish plans to meet said targets and mitigate against climate change [17, 18]. In essence, a carbon offset is a reduction of GHG emissions in one capacity that is used to balance an emission of GHGs in another capacity [18]. In the built environment, carbon offsets are to be used after reduction strategies are fully utilized to achieve a "net-zero" classification across the full life cycle of the building [19]. Lützkendorf & Frischknecht [20] summarize four approaches for achieving "net-zero emissions" buildings. The use of carbon offsets would be appropriate under the Economic Compensation (B) and Technical Reduction (C) approaches for achieving net-zero emissions as defined by Lützkendorf & Frischknecht [20]. However, the use of carbon offsets only ensures a balance of emissions and does not mean a project contributes to net-reductions of GHG emissions globally. For projects to actively mitigate against climate change and contribute to the net-removal of GHGs, they would have to be "Carbon Positive" or "Net-Positive", meaning the project would have to sequester more GHGs than it emits at all stages of the projects life [21]. This "net-positive" designation can be achieved using carbon sequestering materials or investing in offsetting practices that will cumulatively remove emissions throughout the course of the project's lifecycle. It is important to emphasize that carbon offsets, especially those that are off-site, should only be employed after appropriate efforts have been made to reduce and avoid environmental impacts for the project.

A carbon credit is the verified certificate that is used to transfer the carbon offset from one entity to another [18]. Carbon credits can take the form of avoidance or removal credits where an activity is credited with the emissions that are avoided or removed, respectively, from the activity occurring. Carbon credits, and the associated carbon credit market, monetize the cost of emissions to provide an investment that funds carbon avoidance, reduction and capture that would likely not occur without funding. There are a variety of activities that can be considered to offset, sequester or avoid emissions. To be considered a carbon credit, the following criteria must be met the following criteria: permanence, additionality, verified, enforceable, and real [22]. In addition, at COP28 "Core Carbon Principles" were adopted as part of the International Alignment on Carbon Offset standards.

3. Methods

This paper intends to bridge the gap between existing literature related to soil carbon mechanics from the fields of agriculture and ecology, the principles of carbon offsets and the fundamentals for life cycle assessment (LCA) applied within the built environment.

3.1. Review of Principles

Following the introduction of soil carbon mechanics in Section 2.1, this paper explores how soil carbon sequestration (SCS) should be considered within LCAs for the built environment. To answer the research questions for this study, a review of LCA and carbon offset principles has been conducted. Relevant LCA standards are reviewed in Section 4.2 to determine whether it is appropriate to include impacts associated with the landscape within an LCA for a project. Building off the introduction for the use of carbon offsets within the built environment, presented in Section 2.2, Section 4.3 reviews the fundamental principles that govern whether a specific activity or intervention can be considered a carbon offset. The reviews of the LCA standards and carbon offset principles are by no means exhaustive but are intended to provide sufficient context to enable the inclusion of site impacts and associated landscaping considerations within discussions surrounding sustainability and impact reductions for the built environment. Therefore, the reviews reflect current standards and understanding surrounding the use of LCA and carbon offsets within the built environment.

3.2. Case Study Building

The case study project used to illustrate how SCS can be incorporated into LCAs for the built environment is located in the Midwest United States. The case study project includes a new build construction on a rural site located on the border between International Energy Conservation Code (IECC) Climate Zones 6A and 6B. The case study building is a two-story building, designed to blend into the surrounding landscape. The case study pertains to the surrounding site included in the project boundary as opposed to the building located on the site. The site landscape is a historic grazing area that is depleted due to prolonged periods of intensive grazing. Excessive grazing has been attributed to loss of soil carbon [7]. As such, part of the project focuses on restoring the landscape to allow the public to reconnect with the historic land and by doing so increase the soil carbon sequestration (SCS) rates on site. The environmental impacts of the building itself will not be discussed within this study. The project site encompasses 12 hectares (30-acres) of grazing area that is classified as temperate grassland. Projected SOC have been quantified for this grazing area under the assumption that the land management changes from continuous grazing to a rotational grazing pattern. The projections have been estimated based on previous studies [7, 23]. An overview of the site is included in Figure 2.

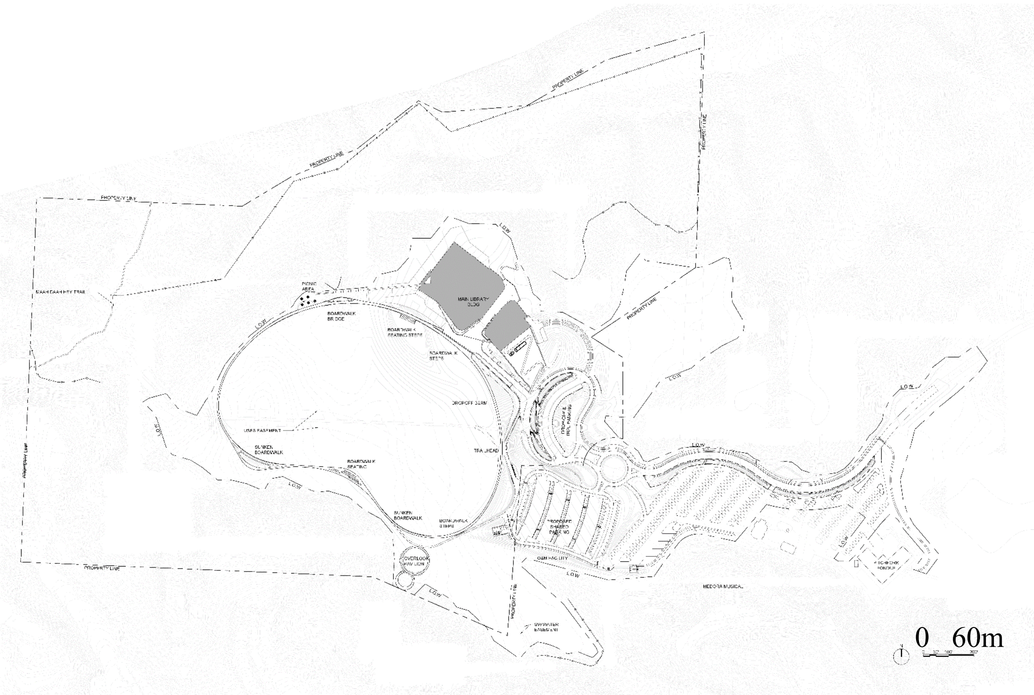

Figure 2: Site plan.

The proposed interventions for the land management of the site have been informed by the historic significance of the site, the local climate conditions, site features and the project goals.

4. Results

4.1. Case Study Soil Carbon Estimates

Initial soil organic carbon (SOC) levels were measured via 21 borehole samples taken across the site [24]. The average SOC for the site was measured to be 5.3 kilograms of carbon per square meter (kg C/m^2) and the average depth of topsoil as 0.2 metres (m) [24]. The total organic carbon (TOC) as a percentage of total organic material (TOM) was measured to be 53% on average across the site. Additionally, the depth-average organic carbon was measured to be 2% averaged across the site. From a review of 50 studies on grazing, Conant et al. [23] found that changes in grazing management could lead to a 10% increase in SOC levels with the soil carbon concentration increasing from 2.6% to 2.9% after 38 years of operation. The soil carbon saturation point for this site has not been estimated as part of this study. In a separate study, Bai & Cotrufo [7] summarize that transitioning from continuous grazing to rotational grazing patterns can lead to a 28% change in soil organic carbon stock on average. The existing SOC and projected estimates for the change in SOC based on Conant et al. [23] and Bai & Cotrufo [7] are presented in Figure 3.

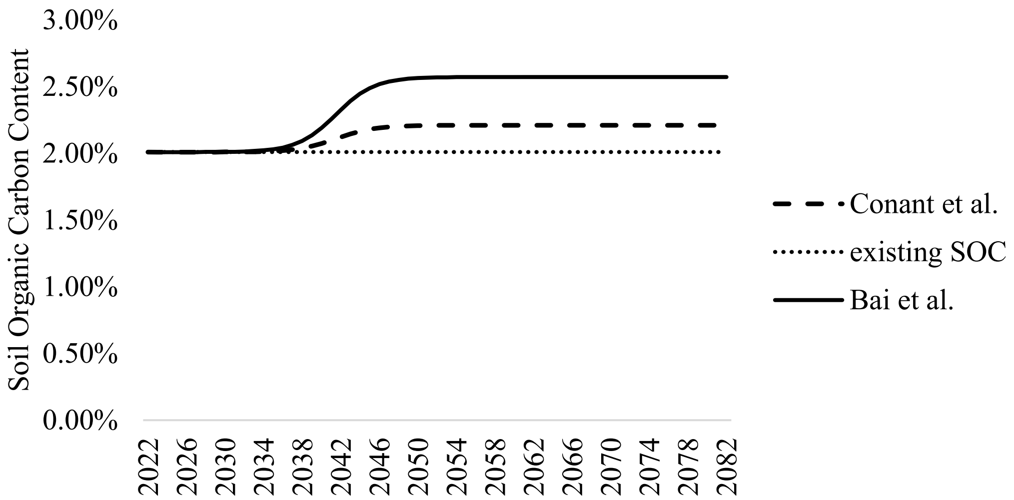

Figure 3. Soil Organic Carbon Concentration for case study site.

The SOC content, in Figure 3, is presented across a 60-year reference study period to be aligned with that for a building. Based on previous studies [7, 11, 12], the SOC is expected to reach a new steady-state within the reference study period that is used to enable comparisons for building-scale LCAs. For the case study site, implementing adaptive multi-paster grazing techniques could lead to approximately 235,000 kgCO_2, for a 10% increase in SOC [23], or 660,000 kgCO_2, for a 28% increase in SOC [7], being sequestered over the entire site over the course of 40 years. This would be approximately 495 kgCO_2/hectare/year for a 10% increase in SOC and 1360 kgCO_2/hectare/year for a 28% increase in SOC on average for 40 years until the new steady-state is reached. If the land management practices do not change after this new steady-state is reached, then this carbon can be considered to be stored in the soil for the duration this management strategy is implemented.

4.2. LCA Principles

The use of life cycle assessment (LCA) within the built environment is governed by ISO 14040:2006+A1:2020 [25] & ISO 14044:2006+A1:2018 [26] for general principles, requirements and guidelines. EN 15804:2012+A2:2019 [27] and EN 15978:2011 [9] provide further guidance and requirements for assessments at the material and building level, respectively. EN 15978 [9], ISO 21931-1 and ISO 21931-2 [28] are the most relevant for the discussion surrounding how SCS and site impacts should be incorporated into project scale assessments for the built environment, if at all. The incorporation of site impacts within LCAs for the built environment depends on the system boundary for the assessment. The system boundary defines what is included within the scope of the assessment [9].

EN 15978 specifies that the assessment includes both the building and its site [9]. For ISO 21931-1:2022 [28], the system boundary is defined to include "the whole building, its services, related external work and its site, for its entire life cycle". Furthermore, ISO 21931-1:2022 provides general guidance regarding the local environmental aspects (clause 6.5.1.3.2) and the local environmental impacts (clause 6.5.1.2.2) that should be included within the assessment. Aligned with ISO 21931-1:2022, site impacts should be included within the assessment if they have: "local impacts on biodiversity and ecology"; "load on local infrastructure"; "effects on the local microclimate"; or "impact on surface drainage". Additionally, local environmental aspects should be included if they lead to: "emission to air"; "emission to surface water and ground water"; or "emission to soil" [28]. Based on these standards, it is expected to include site impacts within the system boundary for a project. However, the descriptions of the life cycle stages are more focused around the activities and processes that take place within the building itself.

4.3. Carbon Offset Principles
Following current practice, a carbon offset would be reported within Module D for a building LCA as it represents a benefit that exists beyond the system boundary of the assessment [9]. For an activity or process to be classified as a carbon credit it must comply with the core principles established by the Integrity Council for the Voluntary Carbon Market (ICVCM) [29]. These core principles are summarized in Table 2.

Table 2: Core Principles for carbon offsets as established by ICVCM [29]

Category	Core Principle
Governance	Effective governance; tracked; transparent; verified
Emissions Impact	Additional; permanent; robust quantification; no double-counting
Sustainable Development	Sustainable development benefits; contribution to net-zero transition

The "emissions impact" category of the ICVCM Core Principles is most relevant in discussions related to LCA. Additionality relates to changes in global emissions compared to a counterfactual when the carbon offset does not exist [30]. In essence, a baseline is established, representing standard practice in the absence of the carbon offset, and the difference between this theoretical baseline scenario and the actual scenario, with the carbon offset, establishes the "additional" reduction of emissions that is achieved via the offset [29]. Permanence is an effort to ensure emissions are not simply avoided or delayed until a later point in time, therefore delaying the effects of climate change rather than contributing to total reductions of emissions [29]. Each type of carbon offset must be quantified using a robust methodology to ensure compliance with scientific understanding, completeness and enable fair comparisons between different entities reporting on the same offset strategy. The principle ensuring no double-counting is aligned with additionality as it seeks to ensure net-reductions of emissions [29]. For an offset to be considered a carbon credit it cannot be claimed by multiple entities, i.e. the issue party can only award the carbon credit once and only one purchasing party can acquire said carbon credit [29]. The field surrounding carbon offsets is rapidly evolving. The methods used to quantify carbon offsets and determine which activities can be classified as carbon credits have evolved over the past few decades are likely to continue evolving as more research is conducted to determine equitable ways of reducing emissions globally.

5. Discussion
To date there is no unified approach for how soil carbon should be considered nor how it should be reported within LCAs [8]. The way in which soil carbon is incorporated within LCAs for the built environment will be influenced by the system boundary of the assessment and the methodology used to quantify the SCS. As such, the following sections have been structured to discuss the nuances surrounding whether SCS could be considered a carbon offset or whether it should be considered within the site impacts reported for a project.

5.1. SCS as an offset
As discussed in Section 4.3, for an activity to be considered a carbon offset it must be additional to what would have occurred if the carbon credit was not purchased, it must be permanent, needs to follow a robust quantification methodology and cannot be double-counted in any capacity [29]. The requirements for permanence and additionality pose a challenge for land-based carbon offset measures. Soil carbon is susceptible to rapid loss of sequestered carbon if the soil is disturbed, which can occur if the land management practices change and the soil is tilled or the land is developed in some capacity [12]. Additionally, Booker et al. [16] highlight that a significant amount of the carbon sequestered in soil after a policy is implemented would have occurred whether the policy was initiated or not.

For SCS to be considered an offset, a rigorous baseline needs to be established that represents the soil carbon levels under normal activities [29]. From this baseline, the "additional" carbon that is sequestered in the soil due to a specific activity or intervention would be attributed as the emissions that are offset and would be calculated according to equation (2). This would ignore the fluctuations of soil carbon levels that result from natural processes and the changes in soil carbon levels that result from a changing climate that would contribute to the total change in SOC as indicated by equation (1). Establishing this baseline is a complex challenge due to the number of factors that can influence soil carbon levels and the interactions between these factors [16]. Current methods can provide robust estimates and projections for soil carbon concentrations under defined scenarios [13]. However, as indicated by Booker et al. [16] among others, it is impractical to differentiate the relative increase in SCS from direct interventions versus natural processes. Figure 4 illustrates the difference between the total change in SOC and the change in SOC from a specific intervention. This lack of a robust delineation between the different influencing factors inhibits classifying soil carbon sequestration and other land-based practices as credible carbon offsets.

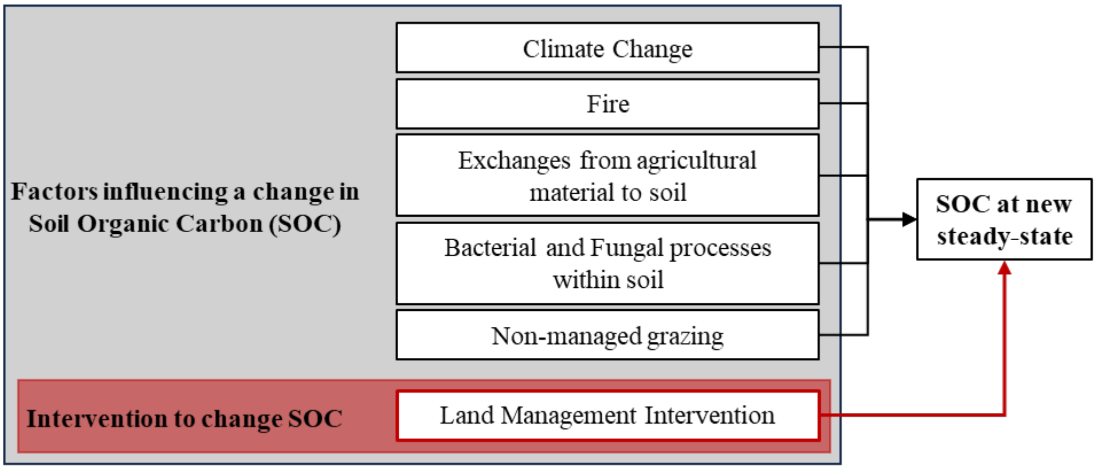

Figure 4. Difference between total change in SOC (equation 1) and the marginal change in SOC (equation 2).

$$\text{Total } \Delta\text{SOC} = \sum_{i=1}^{n} \Delta SOC_{Factor\ i}\, ,\ for\ n\ factors\ that\ influence\ SOC \tag{1}$$

$$\text{Marginal } \Delta\text{SOC} = \sum_{i=1}^{m} \Delta SOC_{intervention\ i}\, ,\ for\ m\ interventions\ that\ influence\ SOC \tag{2}$$

Considering SCS as a carbon offset would be aligned with a consequential LCA (cLCA) methodology, which has seen minimal use within the built environment. cLCA measures the flux of environmental impacts that occurs as a response to a decision or action occurring [31]. Within the context of SCS, cLCA would measure the change in soil carbon that occurs due to a specific activity (i.e. a change in land management practices) and ignores the natural fluctuations in soil carbon that are not associated with the studied activity. cLCA assesses the environmental impacts from marginal changes in processes and activities that exist within an unconstrained market [32]. However, as illustrated by West & Six [12] and Figure 1, soil carbon can reach a saturation point. The understanding of the soil carbon saturation point indicates that soil carbon levels are constrained for a specific site and therefore, not fully conducive with a cLCA methodology.

SCS must meet rigorous criteria for it to be considered a carbon offset. There are multiple influencing factors that influence quantification of the change in SOC attributed to a specific activity or intervention. Quantifying SCS as a carbon offset would result in the marginal change in SOC being determined. However, soil carbon saturation indicates that changes in SOC are potentially constrained and therefore quantification requires more research to determine predictions for the changes in soil carbon levels that result from specific interventions and land management practices.

5.2. SCS as a site impact

As indicated in Section 4.2, it is appropriate to include site impacts within the system boundary for assessments for the built environment. Although a natural system, soil is an intrinsic component of the landscape and therefore it can be included within the materials and processes considered within assessments that consider the environmental impacts of landscapes. If soil carbon is considered within the site impacts, a baseline does not need to be established and the change of soil carbon levels can be reported whether they result from changes in land management, specific interventions or are the result of natural fluctuations in soil carbon. This approach mitigates the concerns outlined by Booker et al. [16] as it measures and tracks the total change in SOC, as illustrated in equation (1), rather than just the marginal change from a specific activity or intervention. Treating SCS as a site impact would follow an attributional LCA methodology which is conducive with current LCA practice within the built environment.

For SCS to be accounted for within site impacts, the initial soil carbon levels would need to be established across the site and a measurement and reporting scheme would have to be established to determine the changes in soil carbon throughout the project's life. For site impacts to be included in LCAs for the built environment, the appropriate life cycle stages, system boundaries and how these site impacts are normalized must be considered.

5.2.1. Life Cycle Stages. The life cycle stages for a project are defined by EN 15978 [9]. These life cycle stages categorise the activities and consumption of resources from different stages of a building's life to provide a uniform approach to reporting a project's environmental impacts. SCS is a natural process that describes the transmission of carbon from the atmosphere to the soil [13]. Module B1, within the use phase, includes the "impacts from normal conditions of use" [9]. The principles of SCS would be aligned with the processes and activities included within Module B1. The processes, activities, material consumption and waste generation from establishing a landscape or site and maintaining it can be correlated to their respective counterparts within the building life cycle stages. The life cycle stage impacts for the site should be reported separately from those for the building to ensure transparent reporting. Future work should categorise site activities to the EN 15978 life cycle stages to ease their interpretation by parties already familiar with the life cycle stages for a building.

5.2.2. System Boundary. Incorporating SCS and other site impacts within LCAs for the built environment would require the system boundary to be expanded to encompass the entire site under study. This would be aligned with the guidance for system boundaries as defined by EN 15978 [9] and ISO 21931 [28]. However, this would move beyond current industry practice that typically focus on the processes and materials within the building enclosure. Expanding the system boundary to incorporate SCS would also require other landscaping, site and maintenance activities to be quantified and reported under a standardised approach. Otherwise, it would be creative accounting to quantify the potential benefits associated with SCS without considering the impacts from maintaining the site and promoting this SCS to occur. Therefore, for SCS to be incorporated into building LCAs, calculation and reporting guidance should be developed to identify which impacts and activities need to be accounted for, how they should be quantified and how they should be reported.

5.2.3. Normalization of Site Impacts. Broadening the system boundary to include site impacts brings another layer of complexity into the already complex challenge of conducting a building-scale LCA. For sites of different sizes to be compared to one another, it is recommended that the site impacts are normalized per area per year (i.e. impact/hectare/year). Additionally, site impacts should be reported separately to those for a building. This would provide a transparent reporting method for the building and site impacts respectively, while also enabling projects with different building-to-site ratios to be compared.

6. Conclusions

Soil carbon sequestration (SCS) is a dynamic process with multiple influencing factors. More rigorous baselines and scenario projections are needed to estimate the additional SCS achieved by implementing different land management practices and interventions to facilitate SCS meeting the core carbon principles, established by the ICVCM, to be considered a carbon credit. Under appropriate land management practices and monitoring, soils can be a viable and natural carbon sequestering resource that should not be overlooked within the built environment. The sites our buildings are constructed on should be considered within discussions and strategies for reducing the environmental impacts of our built environment.

This study has reviewed soil carbon mechanics and the principles of SCS to determine how they relate to life cycle assessment (LCA) methodology and reporting principles for assessments within the built environment. Soil carbon mechanics are well understood within agricultural and ecological literature, however the system boundaries for assessments within the built environment have not considered site impacts, nor the SCS, of the landscape surrounding the building. LCA standards for the built environment (EN15978 & ISO21931-1) indicate the assessment should include both the building and the site. Since SCS is a natural process that can be influenced by various site activities and interventions, it would be appropriate to account for SCS within LCAs for the built environment. Additionally, broadening the system boundary would provide a more holistic view of the environmental impacts of all aspects of our built environment. However, this broadened system boundary will come with added complexities to building-scale LCAs and would require additional normalization metrics to compare projects with different site area and different building-to-site ratios. It is recommended to report site impacts separately from the building impacts to enable comparisons of the building and the site separately. For site and building environmental impacts to be considered together, it is recommended to normalize the environmental impacts based on the ratio of building area per site area.

As indicated by Paustian et al. [11], restoring degraded land has one of the highest GHG reduction rates (measured in Mg CO_2e/ha/yr). The landscape, and its associated environmental impacts, within our built environment should not overlooked as industry strives for greater levels of completeness and accountability when conducting assessments and implementing impact reduction strategies. Projects within the built environment that can stimulate landscape restoration should be encouraged as they provide benefits beyond the discussed GHG reductions. For projects to consider the carbon fluxes within the landscape, initial soil carbon levels will have to be measured and the soil carbon will have to be quantified regularly throughout the use phase of a project to track the change in soil carbon. Based on previous studies, the soil carbon will likely reach a new steady-state within the reference study period used for LCAs in the built environment. Due to the number of factors that influence soil carbon levels and past research, SCS is known to be non-linear and might experience periods where the SCS rate decreases. As such, it is recommended that SCS rates be monitored throughout the operation of the building. Based on current methods, it would be appropriate to quantify variations in SOC using an attributional LCA methodology and monitor the change in SOC throughout the duration of a project.

Regardless of the way in which SCS is considered within building-scale assessments, it is important to consider the existing conditions of the site and local climatic conditions before implementing interventions that might influence the SOC content. Additionally, as indicated by Booker et al. [16], the change in SOC measured after an intervention might be a result of external factors indirectly associated with the intervention as opposed to the intervention itself. Until a greater understanding is established for what interventions can increase the SCS rate under different climate and site conditions, it is advisable to consider soil carbon on a project-by-project basis and consult agricultural literature and bodies of knowledge to inform decisions.

Future work is needed to better predict SCS rates for specific interventions that can be implemented to promote increases in soil carbon levels. Additionally, it is recommended to categorize site activities according to the life cycle stages such that their associated environmental impacts can be reported in a consistent manner. This categorization of site activities should be accompanied by standard quantification methodologies to ensure the associated environmental impacts are quantified to an appropriate level of rigour. In terms of the use of carbon offsets to achieve net-zero designation, additional work is needed to develop guidelines and principles for the scale and types of impact reductions that should be achieved prior to acquiring carbon offsets for a project. The methods used to quantify carbon offsets should be further investigated to determine how they align with LCA methodology to ensure the use of carbon offsets within net-zero claims is appropriate. Additionally, green building certification schemes and other voluntary commitments (i.e. SE2050, architecture2030, MEP2040, etc.) should differentiate between targets that are met from reduction efforts and targets that are met via offsetting.

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