Carbon sequestration and storage potential of urban residential environment – A review

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ABSTRACT

Cities are hotspots of anthropogenic activity and consumption. Thus, the consumption-based carbon footprints of their residents are pronounced. However, the beneficial climate impacts attributable to individual residents, such as carbon sequestration and storage (CSS) provided by residential green spaces and housing, have received less attention in the scientific literature. This review article presents an overview of the current research on the urban residential environment’s CSS potential and argues for its inclusion in the so-called carbon handprint potential of individual consumers. The focus of existing research is on developed countries, and in empirical studies the absence of compiling literature presents a clear research gap. Most current potential is estimated to lie within the carbon pools of residential vegetation, soils and wooden construction, with biochar and other biogenic construction materials presenting key future development pathways. The underlying background variables guiding the formation of a residential carbon pool were identified as extremely complex and interconnected, broadly classified into spatial, temporal and socioeconomic factor categories. Our findings suggest that there is significant potential for growth in the residential CSS capacity, but substantial efforts from the scientific community, urban planners and policy-makers, and individual residents themselves are needed to realise this.

1. Introduction

Carbon budgets have become an important policy tool in climate change mitigation. The IPCC’s Shared Socio-economic Pathway 1–1.9 (SSP1–1.9), which aims to limit global warming to below 2 °C, includes significant measures to increase carbon capture, sequestration and storage in addition to cutting emissions (IPCC, 2021). Similarly, many nations, cities and companies are not only aiming for emission reductions but also “carbon neutrality”, meaning that the remaining greenhouse gas emissions caused by the activities of an area or organisation are compensated by “negative emissions” from carbon sequestration, for example (Laine, Heinonen & Junnila, 2020).

While carbon budgets are now prevalent in policy discussions, there has been less discussion on carbon budgets at the individual level, and the few existing studies only consider the emissions side of personal carbon budgets (e.g. Kalaniemi, Ottelin, Heinonen & Junnila, 2020; Koide et al., 2021). However, similar to cities and nations, individuals can enhance carbon sequestration and storage (CSS) and these positive activities could be included in their personal carbon budgets as negative emissions (Heinonen & Ottelin, 2021). The impact of urban development forms on residential carbon emissions has been well documented in several studies in relation to household characteristics, consumption behaviour and climate change mitigation policies, for example (Fan & Fang, 2020; Gu, Sun & Wennersten, 2013; Ottelin, Heinonen & Junnila, 2018). In contrast, studies directly linking individual carbon budgets to broader urban development patterns from the CSS perspective are virtually non-existent. However, it is justified to presume that similar patterns exist in this regard and several studies on residential CSS potential seem to imply such association (e.g. Chen, Singh, Lopez & Zhou, 2020; Lowry, Baker & Ramsey, 2012; Perkins & Heynen, 2004). As 56% of the global population live in urban areas and the share is expected to increase to 68% by 2050 (He et al., 2021), understanding the role residential landscapes play in climate change mitigation and adaptation, including their CSS capacity, is crucial for sustainable future urban development.

Although the CSS activities of individuals have received little attention so far, the CSS of cities is a growing research area (see reviews by Arehart, Hart, Pomponi & D’Amico, 2021; Küttinen, Zernicke, Slabik

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carbon pool can be viewed as a specific section of the individual consumer carbon handprint, of which boundaries, allocation and magnitude can be defined with relative ease.

The structure of the article is as follows. Section 2 presents the search and selection criteria of the reviewed articles and details the process of analysis and classification of the subject literature. Section 3 showcases the results along with their interpretation, presenting spatial, temporal, typological and thematic trends in the current research, the relative importance of the reviewed elements of residential carbon pool for private consumer handprint, and an analysis of the underlying driving forces. We then discuss these findings further in Section 4, relating them to the broader concept of urban and global carbon budgets and identifying potential research gaps. Finally, in Section 5 we conclude with main findings and implications.

2. Materials and methods

An overview of the approach utilised in identifying and processing the review collection is presented in Fig. 1 and described in detail in the following Sections 2.1 and 2.2.

2.1. Article search

Based on the theoretical framework presented in Section 1, a set of keywords were identified to encompass the subject topic of the review. The keywords were selected to address the carbon pools of green spaces and biogenic materials, carbon sequestration and storage, residential environments, and urban domains. The identified keywords are presented in Table 1.

The articles selected for the review process were sought from the Web of Science core collection database. The utilised date range included a period from the first coverage year of the database in 1945 until the end of 2021. After multiple tests, the following expression of keywords was deemed as best fit and was utilised in identifying the initial articles of interest:

\[ (\text{All fields}) \ "\text{garden}^{\text{+}}" \ OR \ "\text{yard}^{\text{+}}" \ OR \ "\text{soil}^{\text{+}}" \ OR \ "\text{forest}^{\text{+}}" \ OR \ "\text{vegetation}^{\text{+}}" \ OR \ "\text{green roof}^{\text{+}}" \ OR \ "\text{wood}\text{* construction}^{\text{+}}" \ OR \ "\text{wood}\text{* building}^{\text{+}}" \ OR \ "\text{timber}^{\text{+}}" \ OR \ "\text{lumber}^{\text{+}}" \ OR \ "\text{biochar}^{\text{+}}" \ OR \ "\text{bamboo}^{\text{+}}" \ OR \ "\text{hemp}^{\text{+}}" \ OR \ "\text{straw}^{\text{+}}" \ OR \ "\text{biogenic}^{\text{+}}" \ AND \ (\text{All fields}) \ "\text{private}\text{*}" \ OR \ "\text{resident}\text{*}" \ AND \ (\text{All fields}) \ "\text{carbon}\text{*}" \ AND \ (\text{All fields}) \ "\text{urban}\text{*}" \ OR \ "\text{cities}\text{*}" \ OR \ "\text{housing}^{\text{+}}" \].

The search yielded 960 results. To avoid broadening the scope of the review too much, some delimiting boundary conditions for articles were set as follows:

1) Articles needed to be focused on the urban environment.
2) Articles needed to address biogenic carbon sequestration and/or storage either directly or through a clear proxy, such as quantity of vegetation cover.
3) Articles needed to address the residential aspect of the studied carbon pool.

As a result, 207 records were subjected to further screening based on titles, abstracts and keywords. In addition, the so-called snowballing method based on previous benchmark and review articles was utilised to secure a comprehensive review collection. This binomial approach yielded a total of 347 records for eligibility assessment.

In theeligibility assessment, articles were subjected to an initial quick read-through to determine whether their contents matched the aims and previously defined delimitations of the review. Terms for elimination were diverse, and most commonly included a focus on carbon emissions instead of CSS, a focus on other urban sustainability metrics, or an inadequate focus on the residential environment. As a result, 152 records were included for the final article collection and subjected to the qualitative review process.
2.2. Review process

In the review process, an article was first classified to belonging either to the residential green spaces or biogenic housing category based on its main topic. The article was then further classified as addressing either the vegetation or soil aspect of residential green CSS or, in the case of biogenic construction materials, addressing either wooden construction or other more niche topics.

After the initial classification based on topic, review collection was then subjected to a comprehensive read-through where article typology (empirical research article, meta-analysis, review article), geographical location (when applicable) and studied background variables were identified and recorded. Study location was classified at the country level. During the review process, it became apparent that most articles had approached their subject from a certain frame of reference depending on their research field. As such, they usually encompassed a distinct set of studied background variables, which were subsequently classified into spatial, temporal and socioeconomic factor categories. These are addressed in detail in Section 3.3.

3. Results and interpretation

As a result of the review process, a structured overview of the article collection was produced. Most of the research focused on standalone empirical studies, with the compilation of literature being rare. The focal points of the research were clearly on the western and northern hemispheres. Based on the reviewed literature, the natural CSS potential of vegetation and soil as well as the carbon storage capacity of wooden buildings and construction materials were the most well researched aspects. More niche topics included the utilisation of green roof technologies and biochar, as well as other less studied biogenic construction materials such as straw and hemp. Associated background variables affecting the CSS potential of residential environment from individual consumer’s perspective were also identified. These will be discussed further in the following sections.

3.1. Overview of the review collection

3.1.1. Typology and themes of the reviewed articles

The distribution of the reviewed articles by type and identified factors in relation to the studied CSS methods are presented in Table 2. Of the final collection of articles accepted for review, the majority addressed the CSS potential of residential green spaces as their main topic, with the primary focus either on vegetation, soil or both. These included 112 articles or approximately 74% of the final yield. Biogenic housing and construction materials were the main topic of 40, or approximately 26% of the articles. In other words, the residential green space carbon pool was overrepresented in our article collection, whereas the biogenic housing and construction pool received less attention. Subcategory-wise, studies of the vegetation and soil components of the residential green space pool were rather evenly represented, whereas...
articles related to wooden construction far outnumbered those addressing other biogenic materials. It should be noted that several articles addressed multiple subthemes and factor categories; hence the cumulative counts in Table 2 do not correspond to the total number of reviewed articles.

Most of the reviewed articles were empirical studies, the focus of which was limited, often presenting the results of a single case study or research project. Comprehensive reviews and meta-analyses were rare, potentially reflecting the novelty of the topic and CSS research in the residential setting in general (Fig. 3).

All subcategories of the urban residential CSS landscape were relatively equally studied in the temporal factor category, whereas in spatial and socioeconomic categories clear distinctions were observed. Articles on vegetation CSS potential had high representation in both categories, whereas soil and wooden construction received less attention from the socioeconomic perspective and studies of wooden construction materials were clearly lacking from the spatial perspective. This trend was evident in the counts of published studies per study theme and in the relative proportions, presented on the left-hand and right-hand sides of Fig. 2, respectively. A special case was other biogenic construction materials, which were evidently a niche topic, making it hard to construct any accurate interpretations of their representativeness across the factor categories.

3.1.2. Publication dates and subject locations of the reviewed articles

The publication dates of the reviewed articles indicated that the study topic has gained a lot of momentum in the past 5–10 years and the cumulative count of articles has increased rapidly (Fig. 3). With accelerating global warming, climate change mitigation potential and the resilience of urban structures are subjects of growing interest in the research field of the built environment. Residential CSS potential also appears to be experiencing a similar trend.

Of the 131 articles in which the geographical focus could be reliably located to a single continent, the vast majority were focused in the northern and western hemispheres. A clear cluster was present in North America, with a total of 72 published articles, followed by Europe with 43 records. As such, these two areas accounted for approximately 76% of the total article yield (Table 3). Other areas addressed in the reviewed articles included Asia (14 articles), Australia & Oceania (7), South America (3) and Africa (1). It should be noted that one of the articles (Velasco, Roth, Norford & Molina, 2016) addressed both Singapore and Mexico and was hence counted as part of the Asian and North American categories, respectively. In addition, a number of studies addressed multiple CSS methods and hence the cumulative sums in Table 3 do not add up to the total article count.

Multiple factors can explain the overrepresentation of the northern and western hemispheres in the data. These regions generally underwent drastic levels of urban development in the 20th century and a large proportion of their population already inhabits cities. In comparison, studies were lacking in Asia and South America, and were virtually non-existent in Africa, reflecting regions of lower socioeconomic status where the population is still experiencing a rapid shift from rural to urban environments and where the focus of related research is diverted elsewhere (UN, 2019). This is problematic, as the effects of residential land use conversion are currently poorly understood in areas where most future urban expansion is predicted to take place (Ritchie & Roser, 2018; Seto, Güneralp & Hutyra, 2012).

For the current research focus areas, a clear disparity was observed between Europe and North America. In the latter the research has focused on vegetation and soil CSS potential, accounting for spatial and temporal trends as well as intensive urban maintenance practices and socioeconomic influence. In Europe, however, the residential carbon pool studies have focused more on biogenic materials and specifically on wooden construction. The observed divide could be explained by the focus on climate benefits generated by wooden construction, since several European countries have national wood construction schemes to mitigate their environmental impact. This may have invoked increased research needs for and interest in the CSS potential of wooden construction in the region. The majority of the European wooden construction articles were conducted in the Nordic countries, which in turn can be explained by the region’s long forestry industry traditions as well as their strong commitment to environmental activity.

3.2. Carbon handprint potential of the reviewed CSS methods

Sequestration rates of vegetation can be high in urban residential environments, and multi-layered, diverse vegetation has been shown to rapidly improve both above- and below-ground CSS (Edmondson,
Davies, Gaston & Leake, 2014; Fissore et al., 2012; Gu, Crane II, Hornberger & Carrico, 2015). Urban vegetation CSS rates are largely dependant on spatial and temporal factors reflecting the physical environment and past land use activities of the subject location. In low productivity environments, improving the CSS potential with residential vegetation cover requiring intensive maintenance usually results in a net positive carbon sink effect compared to natural background rates (Golubiewski et al., 2006; Jo & McPherson, 1995; Nagy, Lockaby, Zipperer & Marzen, 2014). The initial role of vegetation in establishing a carbon pool at the property after construction is important, as high sequestration rates translate to relatively high above-ground storage at the early stages of parcel-level succession (Davies, Edmondson, Heinemeyer, Leake & Gaston, 2011; Schmitt-Harsh, Mincey, Patterson, Fischer & Evans, 2013).

Soil forms the most substantial urban organic carbon storage, and privately managed urban horticultural areas are shown to hold relatively high densities of soil organic carbon (SOC) (Dobson, Crispo, Bleivins, Warren & Edmondson, 2021; Edmondson, Davies, McHugh, Gaston & Leake, 2012; Pouyat, Yesilonis & Nowak, 2006). Like vegetation, CSS rates of soil are dependant on the spatiotemporal characteristics of the region and are relatively high in comparison to natural rates in cities in arid and semiarid environments (Jenerette, Wu, Grimm & Hope, 2006; Trammell et al., 2020). In addition, some studies have indicated the potential for SOC increases when residential land use conversion has taken place on former agricultural land (Edmondson et al., 2014; Pouyat, Yesilonis & Golubiewski, 2009; Tresch et al., 2018). Soil eventually reaches saturation levels for carbon storage capacity and net sequestration rates become essentially zero, placing limits on the amount of CSS that can be achieved in this manner (Stewart, Paustian, Conant, Plante & Six, 2007; Zirkle, Lal & Augustin, 2011). However, as urban soils are subject to frequent high-intensity disturbances, the SOC storage is rarely saturated and hence they offer significant potential for urban residential carbon handprint improvement (Gough & Elliott, 2012; Peach, Ogden, Mora & Friedland, 2019).

In their study, Koide et al. (2021) estimated that the greatest overall carbon footprint reduction impact for individual residents related to housing would result from the implementation of carbon-negative housing, i.e. a residential building that sequesters and stores more carbon than it releases to the atmosphere during its life cycle. As of now, one of the most feasible ways to strive for this is by favouring biogenic construction materials that contain embedded carbon stored in their structures (Kuittinen et al., 2021; Pittau, Lumia, Heeren, Iannaccone & Habert, 2019). Accounting for entire building life cycles and essentially zero carbon escape from the materials, the resulting long residence times with minimal losses could translate to substantial increases in the urban consumer carbon handprints (Amiri et al., 2020; Kalt, 2018).

Current research on biochar utilisation in residential environments was limited to one study. The results of Ariluoma, Ottelin, Hautamaki, Tuukkanen and Mänttäri (2021) showed that biochar could play a far greater role than trees in enhancing the residential CSS capacity. Both long residence time recalcitrant forms of C and deep cultural layers of high SOC concentration are extremely important for maintaining a robust and temporally stable urban soil carbon pool (Lorenz & Lal, 2015; Vasenev & Kuzyakov, 2018; Vasenev, Stoorvogel & Vasenev, 2013). As such, biochar could be utilised to artificially accelerate the cultural layer development in soil and significantly enhance the residential CSS capacity by locking the embedded biogenic carbon in deep soil layers for a long time.

Green roofs may exhibit vegetation sequestration rates comparable to private gardens and yards (Cascone, Catania, Gagliano & Sciuto, 2018; Sultan, Ahmed, Hossain & Begum, 2021). However, as they typically lack an abundant substrate or woody plants to store the sequestered carbon for longer residence times, their overall CSS potential is limited, unless the sequestered carbon is converted to storage via other means, i.e. biochar production.

In summary, carbon pools of vegetation and soil as well as wooden

Table 3
Number of articles by decadal periods and spatial distribution across continents per study theme. Note that the first column in the table covers two decades (1980–99) and final one only two years (2020–21).

| CSS method                  | 1980–1999 | 2000–2009 | 2010–2019 | 2020–2021 | Africa | Asia  | Australia & Oceania | Europe | North America | South America | Global/Not defined |
|-----------------------------|-----------|-----------|-----------|-----------|--------|------|---------------------|--------|---------------|---------------|---------------------|
| Vegetation                  | 2         | 17        | 47        | 10        | 0      | 10   | 4                   | 12     | 48            | 2             | 5                   |
| Soil                        | 1         | 5         | 42        | 6         | 0      | 3    | 0                   | 12     | 31            | 1             | 4                   |
| Wooden construction materials | 1         | 6         | 24        | 10        | 1      | 1    | 3                   | 24     | 4             | 1             | 6                   |
| Other biogenic materials     | 0         | 0         | 3         | 1         | 0      | 0    | 0                   | 3      | 0             | 0             | 1                   |

Fig. 3. Publication dates and subject locations of the reviewed articles.
buildings seem to offer the greatest potential for residential CSS increases. These are currently well-studied in the subject literature and the conclusion can thus be made with fair confidence. Other biogenic construction materials and biochar could present tremendous opportunities for residential carbon handprint improvement, but current literature on the topic is scarce and related conclusions are therefore uncertain. Green roofs and other structural vegetation solutions offer high sequestration rates but lack storage capacity, and would thus need to be combined with means to convert the sequestered carbon into long-term storage.

3.3. Factors affecting residential CSS

Based on our literature review, we identified three main categories of variables affecting the CSS rate of residential areas. These were broadly classified as follows: (1) spatial factors, (2) temporal factors and (3) socioeconomic factors. Many of the analysed articles addressed more than one factor category, and their exact distributions are presented in Table 1 and Fig. 2.

Spatial factors refer to variables that are location- and space-dependent and can thus vary substantially depending on the scale and region of observation. Temporal factors encompass the historical aspect of the residential carbon pool, referring to changes in CSS over time. Socioeconomic factors incorporate the anthropogenic influence characteristics of urban residential landscape. In the following sections, we briefly discuss these factors and attempt to define their pathways of influence, accounting for potential interactions between the categories.

3.3.1. Spatial factors

Spatial location-dependant environmental variables, such as local climate and soil type, greatly affect the CSS rate of residential green spaces (e.g. Kirkpatrick, Daniels & Zagorski, 2007; Sarzhanov et al., 2017; Selhorst & Lal, 2012). Individual consumers generally have less means of influence over these with growing scale and, as such, variables occurring at macro- or meso-spatial scales often place hard constraints on the CSS potential of residential green spaces. These can be supplemented with intensive management practices, which can in turn overcome many of the environmental limitations occurring essentially at microspatial scales, such as nutrient and water availability (e.g. Golubiewski et al., 2006; Jo & McPherson, 1995; Nagy et al., 2014).

In addition, urban structural metrics such as housing density, land use intensity and parcel land cover outside the housing footprint affect residential CSS potential (Klobucar, Östberg, Wiström & Jansson, 2021; Robinson et al., 2012; Smith, Gaston, Warren & Thompson, 2005). Their relative impact may differ across geographic regions, spatial scales and urban gradient, and they may also interact with variables belonging to other factor categories. Velasco et al. (2016) argued that residential vegetation formed a net carbon sink in Mexico City but an emission source in Singapore, with the discrepancy arising mainly from differences in local typology of urban infrastructure. Godwin, Chen and Singh (2015) showed that the impact of neighbourhood-level environmental characteristics on residential CSS rates increased with housing density. Furthermore, the results of Chen et al. (2020) indicated that the significance of different socioeconomic variables in explaining the residential green CSS patterns varied greatly across the urban gradient. These examples highlight the interplay of urban fabric and demographic characteristics at different spatial scales in determining the residential green space CSS potential.

Unlike the direct CSS of residential green spaces, utilisation of biogenic construction materials for residential carbon handprint enhancement is much less location-dependent, although some materials, e.g. Norway spruce, may be more accessible in some regions than others. Since the carbon storage of biogenic construction materials is embedded, the location of a building does not necessarily present any significance from this perspective. The importance rather lies within the quantity of biogenic materials used (Hafner, Slávik & Storck, 2020). In general, half of the mass of wood-based products is carbon; however, some buildings can store more carbon than others. Amiri et al. (2020) argued that the quantity of wooden buildings is not a sufficient metric for increasing carbon storage in urban areas but rather emphasises the importance of the quantity of wooden products used in an individual building. The more wooden products are used in a building, the greater the carbon content of the structure and subsequently the resulting carbon storage.

3.3.2. Temporal factors

The succession of soil and vegetation carbon pools in the residential setting after initial construction disturbance is crucial from a temporal perspective. Construction activities at a property often deplete vegetation and soil carbon storage, which recovers with time and sufficient management. Thus, property age and past maintenance practices have been observed to influence residential green space CSS potential greatly. For example, Golubiewski (2006), Gough and Elliott (2012) and Schmitt-Harsh et al. (2013) all observed higher average parcel-level carbon storage rates at older properties, whereas the results of Finore et al. (2012) and Boone, Cadenasso, Grove, Schwartz and Buckley (2010) indicated that past maintenance practices can create legacy effects that influence CSS rates for decades. The impact of legacy effects may outlast contemporary trends; for example, Luck, Smallbone and O’Brien (2009) showed that past socioeconomic variables predict an abundance of vegetation cover better than current ones, and Visscher, Nassauer and Marshall (2016) argued that private garden typology is often realised more via past management activities than current residential preferences.

During the initial years after establishment, the role of lawn grass and other herbaceous vegetation in restoring the associated CSS potential is often pronounced, as they can improve the SOC content substantially, although the results of some studies point towards early emission source rather than sink due to construction disturbance and increased soil respiration rates (Pouyat et al., 2009; Sapkota, Young, Coldren, Slaughter & Longing, 2020; Schepelova et al., 2017; Trammell, Pouyat, Carreiro & Yesilonis, 2017). With time, the significance of shrubs and trees grows, overtaking the CSS potential of herbaceous vegetation at more mature properties where abundant tree cover has had sufficient time to develop (Davies et al., 2011; Lowry et al., 2012; Schmitt-Harsh et al., 2013; Timilsina, Staudhammer, Escobedo & Lawrence, 2014). The precipitation of organic carbon from vegetation deeper into the soil increases with time and further enhances the resulting CSS (Contosta, Lerman, Xiao & Varner, 2020; Huyler, Chappelka, Prior & Somers, 2014; Smith, Williamson, Pataki, Ehleringer & Dennison, 2018). At old residential sites, the so-called cultural layers of deep soil may contain extremely high quantities of carbon, although development takes a very long time (Sarzhanov et al., 2017; Vasenev & Kuzakow, 2018; Vasenev et al., 2013).

In the case of biogenic construction materials, sequestration of carbon from the atmosphere takes place at the growing site before the transformation of the resource into a construction material, and this embedded storage remains virtually unchanged throughout its life cycle in the residential setting. This means that the utilisation of biogenic construction materials is functionally an anthropogenic terrestrial carbon flux, transporting the stored carbon from the growing site pool to the residential pool. As such, the resulting increase in CSS capacity is not realised per se until the recovery of growing stock at the harvest site. As the growth rate for typical timber construction wood has been estimated at up to 50 years, it could take substantial time for the corresponding carbon stock gain to be realised in full (Gustavsson, Pingoud & Sathre, 2006; Perez-García et al., 2005). In contrast, many of the other biogenic materials have much shorter growth cycles and they can be utilised to increase the residential carbon stock in a more rapid fashion (Gu, Zhou, Mei, Zhou & Xu, 2019; Pittau et al., 2019; Siddagar, Rai, Jones, Wilhan & Fieldson, 2010). The fast growth rate materials could therefore be utilised for the short-term, high-intensity accumulation of a residential carbon pool, whereas timber construction is best implemented as a
long-term solution with careful policy planning.

In addition, of crucial importance regarding the CSS potential of biogenic construction materials is their utilisation at the end of a building’s life cycle. Research has shown that if wood-based products are not reutilised in a suitable manner at the end of life, the original generated climate benefit will reduce significantly (Börjesson & Gustavsson, 2000; Penaloz, Erlendsson & Falk, 2016; Salazar & Meil, 2009). If wooden products are reutilised as building materials after deconstruction, the embedded carbon will stay locked in the product (Hafner & Schäfer, 2017, 2018). In such recycling scenarios the carbon stock is transported away from the residential pool, and this can enhance the temporal scale of the resulting carbon handprint impact to permanent from a private consumer’s perspective, as the potential further emissions along the supply-residency chain should be allocated to subsequent owners of the carbon pool. If these emissions can be further avoided via circular economy solutions, the utilisation of biogenic construction materials could potentially lock carbon away from the atmosphere for a long time (Edmondson et al., 2014; Salazar & Meil 2009; Takano et al., 2015).

3.3.3. Socioeconomic factors

Socioeconomic factors were an important predictor of residential vegetation and hence CSS capacity in many of the reviewed articles. In general, neighbourhoods of higher socioeconomic status and with higher house prices usually have a higher proportion of vegetation cover (e.g. Allinson et al., 2016; Bigsby, McLane & Hess, 2014; Des Rosiers, Marius, Yan & Villeneuve, 2002; Mennis, 2006; Sander & Zhao 2015). This association has been explained by higher perceived property values with green land cover (Blaine, Clayton, Robbins & Grewal, 2012; Grove et al., 2006), more opportunities for intensive green space management (Klobucar et al., 2021; Troy, Grove, O’Neill-Dunne, Pickett & Cadenasso, 2007), and social norms and lifestyle behaviour (Hunter & Brown, 2012; Visscher et al., 2016).

In their landmark paper, Troy et al. (2007) argued that variables associated with household financial status (e.g. median household income, education level, home ownership status) create the possibility for a high proportion of green land cover and CSS at the neighbourhood scale, which is then realised at private parcel level by individual lifestyle behavioural choices and actions. In other words, economic capital enables abundant green cover, the realisation of which is dependant on consumer preferences. Furthermore, different variable groups can be important depending on the socioeconomic structure of the neighbourhood. For example, the results of Egerer et al. (2018) indicated that financial status-related variables explained SOC density effectively in high-income neighbourhoods, whereas social and cultural norm-related variables were more important determinants in neighbourhoods of limited wealth. Thus, residential CSS capacity seems to be very much related to socioeconomic opportunity and justice. This interpretation is further supported by similar results from e.g. Perkins and Heynen (2004), who demonstrated that homeowners are far more likely to participate in local greening programmes than tenants, Conway, Shakeel and Atallah (2011)), who showed that higher socioeconomic status was associated with higher involvement in residential associations, and Bonilla-Duarte, Gómez-Valenzuela, Vargas-de la Mora and García-García (2021), who observed that private property contributions to total regional green infrastructure were higher in wealthier neighbourhoods.

The global share of wooden residential construction is small compared to conventional materials, even though biogenic construction may incur lower life cycle costs on private consumers (Herjarvi, 2019; Hildebrandt, Hagemann & Thran, 2017; Thomas & Ding 2018). Espinoza, Trujillo, Mallo and Buehlmann (2016) argued that the small market share is due to current market barriers that discourage the use of wood, e.g. lack of producer and consumer knowledge and resulting lock-in effects. Similarly, Gajic et al. (2021) identified numerous potential legislative and consumer perception-related issues for biogenic materials utilisation in retrofits in developing European housing markets. Legislative and economic guidance from policy-makers to address these market failures could prove effective. For example, environmental taxes or subsidies that support the adoption of green construction materials could advance a change towards a greener building sector (Hildebrandt et al., 2017).

Research has shown that private consumers can recognise the environmental and aesthetic benefits associated with wooden construction materials (Gold & Rubik 2009; Kylkilahti et al., 2020; Lahtinen, Harju & Toppinen, 2019). Recently, a price premium was observed for wooden multi-storey residential apartments in Helsinki, the capital city of Finland (Talvitie, Vimpari & Junnila, 2021). This may be an indication of recent increased consumer knowledge regarding the environmental benefits of wooden housing; in other words, a green signalling effect. The green signalling effect can be further argued through a recent study which suggests that wooden houses accommodate on average more environmentally conscious residents (Ottelin, Amiri, Steubing & Junnila, 2021). However, individual consumers may also have sustainability concerns regarding wooden housing, and additional ones regarding the safety, longevity and cost of materials (Haita, Hansen & Nybakk, 2015; Kylkilahti et al., 2020; Larastatie et al., 2018). Perhaps most importantly, a substantial proportion of respondents in many of the reviewed studies expressed that they were not very aware of the aforementioned properties of wooden housing. Thus, better communication about the associated quality parameters, environmental benefits and life cycle costs could improve consumer attitudes and perceptions towards biogenic materials. This could translate into higher related demand, provided that the local industry practices are rooted in transparency and sustainability.

4. Discussion

The results section highlighted the potential of vegetation and soil CSS as well as wooden construction as means for carbon handprint improvement in the urban residential setting. Biochar addition to soil and other biogenic construction materials, albeit possessing great potential, have been scarcely researched and their potential is therefore hard to reliably quantify. CSS rates occurring from green roofs were deemed negligible compared to other identified methods, and their largest beneficial effects in the cityscape would likely be realised via different impact pathways. The studied background variables were recognised as extremely diverse and intertwined, broadly classified into three distinct categories.

In the following sections we briefly shift the focus of discussion from the residential carbon handprint to carbon budgets, in order to estimate the importance of residential CSS in relation to individual and society-wide emissions. We also identify potential research gaps based on the reviewed literature.

4.1. Impact on urban carbon budgets

From an individual resident’s perspective, the CSS potential of the urban residential environment is usually very limited in order to mitigate emissions associated with their consumption-heavy lifestyle (Allinson et al., 2016; Fissore et al., 2012; Herjarvi, 2019). However, the resulting impact could be substantial at the city level. For example, Talvonen and Airaksinen (2018) argued that residential green spaces can provide bottom-up scalability in the cityscape and contribute to ecosystem services, including CSS, more than their individual cumulative value would suggest. Stoccero, Sendon, Falshaw and Edwards (2017) calculated that using timber for Auckland’s predicted residential housing growth until 2040 could improve the speed at which associated emission reduction targets are achieved by more than 18%, and Churkin et al. (2020) demonstrated that increasing wood-based construction globally could increase urban carbon storage levels by 170%. As energy production systems are targeted at carbon neutrality (IEA, 2021)
and buildings for better energy efficiency (UNEP, 2021), the relative importance of residential carbon handprints in the climate change mitigation of the built environment is likely to increase in the future.

The ‘carbon cost-effectiveness’ of individual elements of a residential carbon pool varies across green infrastructure typologies and biogenic construction materials, depending on the speed and size of the associated CSS impact and the global warming potential of related emissions. For example, trees and shrubs generally require less intensive maintenance and contribute more towards CSS than lawns, and other biogenic materials may have lower production chain emissions and higher regrowth rates compared to wood (Churkina et al., 2020; Fissore et al., 2012; Horn, Escobedo, Hinkle, Hostetler & Timilsina, 2015; Pittau et al., 2019). As such, the shift in consumer preferences towards diverse vegetation structures and multifaceted biogenic construction could improve the resulting impact on residential carbon budgets.

In addition to a direct CSS impact, improving the residential carbon handprint can produce multiple beneficial rebound effects on urban carbon budgets. For example, green infrastructure may act as an insulating element in a cityscape and can mitigate the urban heat island phenomenon, as well as regulate residential building indoor temperatures, which can reduce cooling-related operational emissions substantially (Cameron et al., 2012; Shaﬁque, Xue & Luo, 2020; Sultana et al., 2021). Lower production emissions associated with biogenic construction materials compared to conventional ones and increased opportunities for circular economy solutions could offset some of the residential housing carbon footprints (e.g. Gu et al., 2019; Högmeier, Weber-Blaschke & Richter, 2013; Takano et al., 2015; Tsunetsugu & Tonosaki, 2010). Individual consumption and time use could also shift towards less emission-intensive alternatives regarding garden maintenance, agricultural produce consumption and leisure activities (e.g. Ding et al., 2016; Edmondson et al., 2020; Kirkpatrick & Davison, 2018).

However, increasing the allocation of space for residential CSS could also result in emission increases related to green space maintenance and urban sprawl (e.g. Aydin & Cukur, 2012; Gu et al., 2015; Horn et al., 2015; Resch, Bohne, Kamsdal & Lohne, 2016) and the utilisation of biogenic construction materials needs to be accounted for related regrowth times, displacement factors and technological developments in the energy production sector (Churkina et al., 2020; Gustavsson, Joelsson & Sathre, 2010; Seppälä et al., 2019). In addition, the impact on the CSS potential of undeveloped land, the opportunity costs of lost agricultural potential, as well as the land-supply chain efficiency of different biogenic materials need to be considered (Goswein, Reichmann, Habert & Pittau, 2021a).

In the context of global emissions, the absolute value of urban residential CSS is evidently small. Urban built land cover has been estimated globally as approximately 0.5–1% of total terrestrial land (Pesaresi et al., 2016; Ritchie & Roser, 2019; Schneider, Friedl & Potere, 2009). The total resulting carbon sink effect and its capability to mitigate global emissions will as such fall very short compared to total global forest land potential, for example. However, the value is more so realised when residential land and housing CSS rates are compared to the corresponding shares of global emissions. It is estimated that urban sprawl will continue at a high level in the future globally, presenting carbon emissions (Gao & O’Neill, 2020; IEA, 2019). Residential land use and buildings are major contributors to these emissions, as they can occupy around 40–90% of the total urban built area and represent approximately 60–90% of total building stock, depending on location (e.g. Kasanko et al., 2006; European European Commission, 2013; Toure, Stow, Clarke & Weeks, 2020). Mitigation actions aimed at improving the residential environment’s carbon handprint potential by increasing the CSS rates of green spaces and housing could therefore have a substantial impact on the related subsections of urban carbon budgets, thus proving meaningful even on the global scale (e.g. Amiri et al., 2020; Birge & Berger, 2019; Ottelin et al., 2021; Zhao et al., 2013).

Despite being beyond the scope of this paper, it is worth mentioning that residential CSS enhancement may result in beneficial impacts on other sustainable city metrics. These include enhanced urban biodiversity and invasive species mitigation potential, socioeconomic benefits via improved opportunities in the local housing and labour markets, and carbon offsetting opportunities, amongst other things (e.g. Edmondson et al., 2020; Goswein et al., 2021b; Himes & Busby 2020; Lehmman, 2007; Rüdd, Vala & Schaefer, 2002; Stocchero et al., 2017). These co-benefits and potential trade-offs need to be carefully considered by policy-makers and urban planners for residential carbon handprint improvements to result in surplus benefits for urban carbon budgets and the environment in general.

4.2. Implications for future research

As was evident from Table 2, the vast majority of published research on the residential carbon pool has been empirical, with reviews and meta-analyses being equally rare. Thus, more effort should be directed towards compiling and synthesising the existing literature of the field to identify common themes and issues as well as potential novel approaches. The review presented here contributes to filling this gap but is by no means exhaustive. The subject literature provides multiple perspectives and scales that could be investigated further with precisely targeted research. The scope of this paper was too broad to account for each of these nuances.

The spatial distribution of the review collection raised a clear issue related to the lack of data from rapidly urbanising regions. As such, future research action should aim to address this disparity by placing more focus on the less researched urban environments of Africa, Asia and South America. These previously scarcely studied regions may present unique local characteristics that can alter the residential carbon pool in ways hitherto unseen in the current literature. Furthermore, they may provide novel opportunities and knowledge for related climate change mitigation.

The review collection encompassed a wide range of articles from diverse thematical and typological backgrounds, and as such the related methodological approaches in determining residential CSS potential varied substantially. Mainly, a clear divide was observed between the literature on residential green space and housing categories, as studies belonging in the former had often implemented approaches from the field of natural sciences, whereas in the latter study designs were more primed towards engineering sciences. Future endeavours in the field could aim to bridge this observed research gap, employing hybrid approaches from both fields to provide more accurate estimates on the CSS potential and carbon budget of the urban residential environment.

In addition, a clear gradient in methodology with the scope of research was observed. Small-scale studies often employed a traditional LCA- or ﬁeld study-based approach, aiming to quantify the CSS potential as accurately as possible to tackle specific research questions (e.g. Salazar & Meil, 2009; Sapkota et al., 2020; Smith et al., 2005). In contrast, studies aiming at quantifying residential CSS potential from the neighbourhood to the global or system level more often adopted coarser, GIS-, remote sensing- or theoretical modelling-based approaches (e.g. Churkina et al., 2020; Raciti, Huyra & Newell, 2014; Vasenev & Kuzyakov, 2018). As such, the former were often better at quantifying the residential CSS potential precisely, whereas the latter produced more accurate estimates on regional level trends. Future research could aim at integrating the strengths of both approaches, for example by utilising existing case or ﬁeld study data to estimate the residential CSS capacity on a regional scale with spatial predictive modelling.

Regarding methodology, future research on the topic should aim at the widespread application of novel GIS-, remote sensing- and machine learning techniques. These research fields are undergoing rapid development and provide multiple potential approaches to be utilised for residential CSS mapping (e.g. Odebiri et al., 2021; Plozajz-Mazurek, Ryńska & Grochulska-Salak, 2020; Sankey et al., 2021). They may also
present new opportunities to decouple anthropogenic impact from natural processes and to better recognise and manage the underlying socioeconomic driving forces of research topics of high importance in the urban residential environment (e.g. Guo, Zang & Luo, 2020; Nishant, Kennedy & Corbett, 2020; Nunes et al., 2022).

Several studies have aimed at quantifying the carbon budget impact of residential green or wooden housing by comparing the presented estimates of consumption-based emissions either at the individual or national level or to direct production-based emissions at the residential neighbourhood. However, such study designs essentially present a false equivalence by comparing a small portion of the carbon handprint to the total carbon footprint, or by neglecting the associated consumption-based emissions. Thus, future endeavours in the field could address this by comparing the CSS potential of the residential environment with the related consumption-based emissions of housing and maintenance activities, providing a more accurate estimate of the topic.

The current consumer carbon footprint and individual carbon budget literature lacks discussions on the CSS potential of individuals (Ottelin et al., 2019). This is likely related to the limitations of typically used research materials. An individual’s climate impact is usually measured by consumer carbon footprints, which consist of the life cycle emissions caused by the consumption of goods and services. The vast majority of consumer carbon footprint studies are based on household budget surveys (HBS) and consumer expenditure surveys (CES), which are systematically collected in many countries (Heinonen et al., 2020). However, the focus of these surveys is on consumption, and they do not usually include questions that would enable the assessment of the positive activities that consumers can take to enhance carbon sequestration and storage (CSS) (Heinonen & Ottelin, 2021). The situation could be improved by adding such questions to expenditure surveys, or using additional information sources, for example, in order to form a more accurate view of the climate impacts and mitigation potential of individuals.

Biochar and other biogenic construction materials besides timber remain understudied in the field, despite presenting a substantial opportunity for CSS enhancement in the urban residential environment. Future research on the subject should allocate more focus in these areas.

Market analysis research on wooden and other biogenic construction materials from a housing markets perspective is currently lacking. As a result, future efforts could aim to quantify and verify the pioneering results of Talvitie et al. (2021). Furthermore, even though the impact of residential green spaces on housing markets has been previously studied, most of the research is dated (e.g. Des Rosiers et al., 2002; Dom-brow, Rodríguez & Sirmans, 2000; Morales, 1980) and lacking in the sense that it does not aim to quantify whether the observed positive impact on prices translates to higher CSS rates. This could be incorporated in future research on the subject in the urban economics research field.

5. Conclusions

The aim of the review was to identify the most prominent methods for urban residential CSS enhancement, along with associated explanatory variables. To achieve this, a comprehensive literature review encompassing the CSS potential of residential green spaces and housing in the urban domain was conducted. As suggested by the multitude of related variables and carbon budget rebound effects, the issue of improving urban consumer carbon handprints in their residential environment is extremely complex. Both concrete efforts from urban planners and policy-makers as well as more subtle social and preferential changes from individual consumers are needed to implement the full potential of private residential CSS. The role of multidisciplinary scientific research is crucial in this pursuit.

Based on the reviewed literature, the most prominent methods currently available for residential CSS improvement include (i) direct uptake of carbon into vegetation and soil, and (ii) utilisation of wooden construction materials in residential housing. Both approaches have been thoroughly studied in the scientific literature and their impact mechanisms and magnitudes have been reliably quantified. In addition, great potential seems to lie in the utilisation of biochar in soils and other biogenic materials in construction. However, more research on these topics is needed to better understand not only the potential but also the practicality and consumer willingness to adopt these strategies for residential carbon handprint enhancement. In contrast, the CSS potential of green roofs and walls seems to fall short compared to the other mentioned methods, and their utility in the urban residential environment is primarily realised via other impact pathways.

The complex, intertwined nature of the urban landscape makes it difficult to discern the most important individual background variables affecting the residential CSS potential. Rather, the influence of distinct variables and factors differs across space and time. For example, the explanatory power of climatic variables is strong when comparing residential locations across continents, whereas spatial variables of smaller scale, such as topography and nutrient availability, are more likely to explain the differences in CSS potential between neighbourhoods. Vegetation succession and associated temporal variables have minimal influence in young parcels, whereas they might be the most important factor group in old, historical neighbourhoods. Socioeconomic variables present opportunities and guide consumer behaviour in relation to CSS, which may overtake natural limitations and create legacy effects that persist over decades.

Consumer carbon footprints have been observed to differ significantly across cities in the same country, and urban structure seems to be capable of creating lock-in effects in this regard (Koide et al., 2021). Based on the literature review, a similar trend is implied to be present in carbon handprints, where local and regional differences in urban development form, national or city policies, and urban planning practices may influence the residential CSS potential greatly (e.g. Boone et al., 2016; Gajic et al., 2021; Mitchell et al., 2018). To ensure high CSS capacity across the urban residential fabric, policy-makers and city planners should consider the presented spatial, temporal and socioeconomic factors and compose the legislative guiding instruments accordingly. This can be achieved by encouraging appropriate zoning and architectural practices, removing legislative limitations, and improving the construction sector’s ability and willingness to utilise biogenic materials, for example. However, more research on the topic is needed to better understand how urban development patterns tie in with individual consumers’ total carbon handprint potential, and not just the residential CSS aspect.

The key future development pathways for further improving the residential CSS capacity in urban environments include (i) diversification of residential green space typologies, (ii) biochar addition to soil, and (iii) versatile use of a multitude of biogenic construction materials in the private housing markets. It needs to be emphasised that these represent end goals rather than methodological approaches. The attainment of (i) can be advanced by improving socioeconomic equality and opportunity in the citiescape, for example, (ii) by providing financial incentives for private consumers and construction companies to utilise biochar in landscaping activities, and (iii) by increasing consumer knowledge and removing legal barriers to biogenic construction materials adoption. As such, the role of cross-cutting scientific research that incorporates elements from the fields of natural, engineering and social sciences is of utmost importance in determining the best practices and approaches for residential carbon handprint optimisation. Biochar and wall integration lack a compact definition in scientific and legislative literature at the moment, and has been defined as “An indicator of climate change mitigation potential” (Pajula, Vatanen & Pihkala, 2018) or the emission reduction potential of an alternative product (Grönnman et al., 2019), for example. Here, we propose the utilisation of the term in relation to the more established carbon footprint to reflect the opposite portion of carbon budgets and demonstrate its application through the urban consumer carbon pool consisting of residential green spaces and
housing. This approach would provide individuals, communities and the private sector with better means to account for the beneficial impact they have on climate change mitigation, along with the well-documented methods for detrimental impact measurement.

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Declaration of Competing Interest

The author(s) 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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