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Green roofs: environmental contributions with an emphasis on carbon sequestration

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A B S T R A C T

The impermeabilization of the soil by concrete and asphalt, resulting from the urbanization process, has caused the loss of natural vegetation. These modifications have contributed to the increase in the emission of greenhouse gases (GHGs), in particular carbon dioxide (CO_2). Although it is still portrayed today, it is not new that the global concern about climate change has gained prominence on the international political agenda, as an example, the United Nations Conference on the Environment and Development (Rio 92), Kyoto Protocol (1997) and more recently, the Paris Agreement (2015). All of these having as main objectives, the achievement of sustainable development and the reduction of global warming. Given this, green roofs stand out as a promising alternative for cities, given that they have many environmental, ecological and economic advantages, such as, for example, in the reduction of rainwater runoff, mitigation of urban heat island phenomena, creating spaces for the creation of food in urban areas, providing a natural habitat for animals and plants, in addition to reducing atmospheric carbon dioxide, through carbon sequestration. Although the topic “carbon sequestration” is studied all over the world, little is known about carbon sequestration in green roofs. Therefore, this article brings a critical and current bibliographic review on this subject.

Keywords: Urbanization, CO_2 emission, sustainability, global warming.

Telhados verdes: contribuições ambientais com ênfase em sequestro de carbono

R E S U M O

A impermeabilização do solo por concreto e asfalto, proveniente do processo de urbanização, tem ocasionado na perda da vegetação natural. Estas modificações têm contribuído para o aumento da emissão dos gases de efeito estufa (GEEs), em especial, o gás carbônico (CO_2). Apesar de ainda ser retratado atualmente, não é de hoje que a preocupação mundial no que diz respeito às mudanças climáticas, tem ganhado destaque na agenda política internacional, podendo citar como exemplo, a Conferência das Nações Unidas sobre o Meio Ambiente e o Desenvolvimento (Rio 92), Protocolo de Kyoto (1997) e mais recentemente, o Acordo de Paris (2015). Todos os estes tendo como objetivos principais, o alcance do desenvolvimento sustentável e a redução do aquecimento global. Frente a isso, os telhados verdes se destacam como uma alternativa promissora para as cidades, tendo em vista que apresentam muitas vantagens ambientais, ecológicas e econômicas como, por exemplo, na redução do escoamento de águas pluviais, mitigação dos fenômenos de ilha de calor urbana, criação de espaços para criação de alimentos em áreas urbanas, fornecimento de habitat natural para animais e plantas, além de proporcionar na redução do gás carbônico atmosférico, por meio do sequestro de carbono. Apesar do tema “sequestro de carbono” ser estudado em todo o mundo, pouco se sabe sobre o sequestro de carbono em telhados verdes. Sendo assim, o presente artigo traz uma revisão bibliográfica crítica e atual sobre esse assunto.

Palavras-chave: urbanização, emissão de CO_2, sustentabilidade, aquecimento global.

Introduction

The transformations resulting from the urbanization process, in recent years, have caused extreme climate changes, causing great impact worldwide (Ray et al., 2021). The development of urban infrastructure and buildings increased impervious surfaces and, consequently, resulted in higher temperatures in urban centers, a phenomenon known as urban heat island (UHI) (Arenandan et al., 2022).

Associated with these environmental changes caused by urbanization, it also increased the concentration of atmospheric pollutants, including carbon dioxide (CO2). According to the

Intergovernmental Panel on Climate Change (IPCC), global average concentrations of CO2 increased by 19 ppm between 2011 and 2019, which was closely associated with rising global temperatures (IPCC, 2021).

Thus, strategies have been investigated and developed in order to reduce the environmental damage caused by the high concentration of atmospheric CO_2, among which the use of green roofs stands out (Seyedabadi et al., 2021). In addition to the environmental benefits through improved air quality, green roofs also positively impact rainwater retention, thermal comfort, in addition to adding aesthetic and economic value to buildings (Mohapatra et al., 2021).

Green roofs can be categorized according to weight, substrate layer thickness, water requirement, plant species, utility, construction and maintenance costs, which can be intensive, semi-intensive and extensive (Liu et al., 2021). In addition, it consists of basic components, such as: thermal insulation layer, root barrier or waterproofing layer, protection layer, drainage layer, filter layer, soil or substrate layer and vegetation layer (Mohapatra et al., 2021).

Therefore, due to the scarcity of works that address the theme of using green roofs as a carbon sequestrant, the objective was to present the historical context, characteristics and use of green roofs, the consequences of the urbanization process, and emphasize the use of green roofs as sources capable of contributing to carbon sequestration.

Development

Consequences of the urbanization process against the greenhouse effect

Currently, changes in land use and the great advance in urban development have caused vegetation and soil to be replaced by concrete and asphalt. These changes, when associated with deforestation and loss of biodiversity, contribute to an increase in the emission of greenhouse gases (GHG), which can further accentuate climate change on the earth. In addition, the intense urbanization process combined with the alteration of the original landscape, changed the behavior of temperatures in urban centers, causing such areas to present higher temperatures when compared to less urbanized areas, an effect called "heat island" (Rocha et al., 2017).

This temperature increase is mainly caused by gases stored and re-emitted by urbanization complexes that concentrate materials of great energy potential, such as the activity of industries and the vast use of vehicles that have been causing changes in the atmosphere through a continuous increase in pollutants from the air, in addition to the replacement of natural surfaces by buildings such as streets and avenues, which favor the waterproofing of soils and the radiation of heat into the atmosphere (Mendes et al., 2019).

According to Oliveira et al. (2017), among the main consequences caused by heat islands, the increase in temperature, the increase in the concentration of pollutants, and the decrease in relative humidity stand out. Also according to the same authors, heat islands can modify air currents and precipitation, which can be influenced by the type of meteorological system prevailing in the analyzed location, its geographical position, and the structure of buildings.

Heat islands cause thermal discomfort, which can cause some health problems, for this it is necessary to diagnose them to alleviate their effects on the urban environment and, consequently, on the quality of life of the affected population (Ortiz Porangaba, Teixeira and Amorim, 2017).

It is not new that global concern about climate change has gained prominence on the international political agenda, such as the United Nations Conference on Environment and Development (Rio 92), in which the Framework Convention was established of the United Nations on Climate Change. Another important milestone was the Kyoto Protocol (1997), in which it was defined that countries that ratified it should reduce greenhouse gas (GHG) emissions by 5%. More recently, the 2015 Paris Agreement had as one of the measures “strengthening the global response to the threat of climate change” (Rodríguez, 2015; Santos and Silva, 2018).

The Paris Agreement entered into force in 2016, after much resistance and little effectiveness in tackling climate change under the Kyoto Protocol (Oliveira, 2019). Through this agreement, the international community pledged to limit the rise in temperature below 2°C and to continue efforts to limit the rise in temperature to 1.5°C (Rei, Gonçalves and Souza, 2017).

It is noteworthy that regardless of human action, the greenhouse effect exists naturally, as it is a natural phenomenon that occurs for the thermal heating of the earth. If this phenomenon did not exist, the earth would be very cold to the point of making life impossible (Wallace and Hobbs, 2006).

However, man's action on the biosphere to obtain food, deforestation, excessive use of fossil fuels, caused the degeneration of the environment, resulting in the planet's temperature being raised significantly, which is strictly linked to global warming, accentuating the greenhouse effect (Brito et al., 2018). The occurrence of the greenhouse effect is mainly due to the emission of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), in addition to chlorofluorocarbons (CFCs) and water vapor. Among them, CO_2 is the gas that most contributes to the greenhouse effect, due to the large amount that is emitted, reaching an average of 55% of the total (Cerri et al., 2007).

Faced with this problem, the need to measure the total emissions of greenhouse gases (GHGs) emerged. The carbon footprint represents this determination, which according to Gonçalves et al. (2018), through this, it becomes possible to quantify the gaseous emissions relevant to climate change associated with human production or consumption activities. As a result, government entities and organizations have sought to reduce emissions of these gases and the environmental impacts caused (Magri and Baião, 2015).

The increase in GHG emissions and the consequent global warming of the planet have led to the search for strategies aimed at reducing the sources of these gases (Carvalho et al., 2010), such as improvements in energy efficiency, large-scale production of biofuels and reforestation, all to increase the potential for carbon sequestration (Schaeffer et al., 2006). The term carbon sequestration refers to the process that removes and stores carbon from nature by natural or artificial means (Shiferaw, Hurni and Zeleke, 2013), as well as preventing the emission of greenhouse gases from ecosystems (Silva et al., 2003).

Other alternatives are also mentioned by Brito et al. (2018), to partially reduce the emission of carbon into the atmosphere, highlighting: conservation of carbon stocks in soils, forests, and other types of vegetation, preservation of native forests, implementation of forests and systems agroforestry and the recovery of degraded areas.

Since the Kyoto conference, vegetation has received more and more attention as it is a potential means of capturing atmospheric carbon dioxide (CO_2) (Oliveira, Ganem and Baptista, 2017). In the photosynthesis process, the plant can absorb light energy from the sun and transform it into food such as carbohydrates and form oxygen, in addition to being important for the maintenance and sequestration of carbon in the atmosphere (Barbosa et al., 2013; Rocha et al., 2017).

Solutions to this problem

Several works have been carried out to study sources capable of reducing the projection of carbon dioxide (CO_2) into the atmosphere. Brito et al (2018), when evaluating the carbon stock in cerrado soils, could observe that soils that had degraded pasture and agroecological garden provided better carbon stock and credit, especially in soils that had degraded pasture because the roots are closer to the surface.

According to Lal, Negassa and Lorenz (2019), the soil presents itself as an important contributor to carbon sequestration, as it presents benefits such as advances in food and nutritional security, increased renewability, and water quality, and improved biodiversity. The same authors also point out that the level of carbon in the soil is influenced by land use, soil management and the type of agricultural system adopted.

Sheng, Zhan and Zhu (2016) investigated the carbon sequestration potential of biochar using rice straw, in six soils with different pH levels produced in different pyrolysis. In general, through the study, it could be observed that the carbon sequestration potential of biochar reduced along with the decrease in soil pH, especially in the short term and that, in addition to soil pH, other factors such as the content of clay and the experimental duration, also affected the physicochemical and biotic processes of the carbon sequestration dynamics.

Given the importance of forest ecosystems, Chu et al. (2019), in their studies analyzed the forest carbon sequestration in regions of thirteen provinces of China, during the years 1990 to 2015. Through this, they could observe that the forests in the study region had a strong capacity for carbon sequestration and that, in general, carbon sequestration showed a decreasing trend, with a reduced rate of 1.92% during the period from 1990 to 2015.

In addition, studies have been developed using microalgae as a potential source in reducing atmospheric CO_2 emissions, given that they have a good photosynthetic capacity, capable of generating biomass and capturing carbon (Ranjana, Swati and Bhattacharjee, 2018).

Iasimone et al. (2017), developed a study in wastewater treatment plants, using microalgae, to observe the potential for fixation and removal of CO_2 in autotrophic biomass, at different rates of CO_2 fluxes (0.2; 0.4; 1.0 L min^{-1}). Through this, the authors observed that the highest efficiency, equal to 83% of CO_2 fixation was available for the lowest gas flow (0.2 L min^{-1}), while the highest CO_2 removal rate of 24,6 mg L^{-1} min^{-1} was reached for the highest gas flow (1.0 L min^{-1}), thus proving the efficiency in the use of microalgae when under the conditions of the given study.

The occurrence of the urbanization process has favored the increase in the emission of greenhouse gases, this increase is largely contributed by the presence of urban buildings, which contribute to the formation of heat islands.

In this regard, green roofs are considered one of the most suitable sustainable solutions to resolve issues related to urban heat islands, as they have some benefits such as reduced energy savings, thermal insulation, shading, evapotranspiration, in addition to mitigating greenhouse gas emissions (Besir and Cuce, 2018).

In works by Razzaghmanesh, Beecham and Salemi (2016), the potential mitigation effect of heat islands in the city of Adelaide-Australia was evaluated. The results showed that existing materials with low albedos, such as asphalt, metallic roofs, and brick pavements, contribute to the heat island potential. Furthermore, urban development and the lack of natural vegetation contribute to the increase in temperature in cities. On the other hand, when compared to green roofs in the same urban environment, it could be observed that they presented a significant cooling of the environment, in addition to that they can act as an insulating layer to keep buildings warmer in winter.

Historical context of green roofs

The hanging gardens of Babylon (500 BC) are considered one of the first examples of vegetation systems in buildings (Vijayaraghavan, 2016). Similar to Babylon, the Roman and Greek empires also employed these systems. In the Mediterranean region, different plants were used on the buildings to provide cooler and more comfortable interior conditions for the occupants (Besir and Cuce, 2018).

The use of blueprints on buildings expanded considerably in the UK and Central Europe during the 17th and 18th centuries. In the 19th century, despite other European regions and North American cities turning ornamental elements as a center of attraction for residents in urban areas (Manso and Castro-Gomes, 2015), there was a consensus among the urban population that living walls and green roofs were not compatible with modern architecture, due to adaptation difficulties. However, in the mid-20th century and early 21st, due to technological developments, increased levels of occupant comfort, and social awareness of environmental issues, green systems have been at the center of interest year after year (Cuce, 2016).

It is currently well documented in the literature that green roofs and facades have great potential to provide energy savings in the construction sector and thermally attractive and comfortable indoor and outdoor conditions (Cuce, 2017).

In recent years, some countries such as the USA, Canada, Australia, Singapore and Japan have introduced new standards for the economic and energy-efficient profitability of existing buildings, using vegetation systems (Besir and Cuce, 2018). As a consequence of the new regulations, 15% of the roofs located in Switzerland were covered by vegetation systems (Townshend and Duggie, 2007), which represents 4 GW/year in energy savings. A similar regulation was carried out by Canada, in which vegetation systems have to cover between 20 and 60% of the roof, in situations where the floor area of the building exceeds 2000 m_2 (Besir and Cuce, 2018). In Japan, private and public buildings with floor areas that are larger than 200 m_2 must be covered by plants by at least 20% (Chen, 2013).

On the other hand, in Brazil, incentives for the use of vegetation systems are still few and incipient, mostly in the form of bills. For example in Recife, Pernambuco, according to Law No. 18,112/2015, determines that multifamily housing projects with more than four floors and non-residential buildings with more than 400 m² of coverage area must provide for the implementation of green roofs. Another example in Brazilian territory is the municipality of Blumenau, Santa Catarina, whose Complementary Law No. 1,174/2018, reduces the permeable area of land from 20% to 10% if there is an increase in the equivalent area for green roofs in the building (Feitosa and Wilkinson, 2018).

Characteristics of green roofs

Green roofs, also known as green roofs, green roofs, eco-roofs and green roofs. They are characteristic of being constituted by a vegetal covering, composed of grass or other vegetal species, implanted in conventional roofs or slabs (Souza, Ferreira and Vasconcelos, 2015).

Overall, green roofs account for 20 to 25% of global urban areas (Raji, Tenpierik and Van Den Dobbelsteen, 2015). Studies carried out by Ohnuma Junior, Gomes and Silva (2017), in which they carried out a mapping of research locations with green roofs, could prove that developed countries lead researches with the use of green roofs, with emphasis on the United States. Also according to the same authors, Brazil is in fourth place in studies of green roofs.

Green roofs are capable of providing several benefits, among which the following can be mentioned: reduction of greenhouse gas emissions, air pollution, and urban heat island; preventing acid rain; minimization of flood risks, as it retains excess water, providing better habitat for urban life; absorption of local noise pollution within urban areas and improving the durability of internal membranes (Coma et al., 2016; Karteris et al., 2016). In addition to these, another additional benefit that can be cited is that green roofs can improve the health of residents in the urban district (Besir and Cuce, 2018).

Furthermore, the use of green roofs converts the impermeable areas of a roof into multifunctional spaces through the vegetation used (Karteris et al., 2016). For this reason, green roofs are widely used in urban areas (Coma et al., 2016; He et al., 2016).

As for the design of the green roof, it has several basic components that make up its structure. In addition, there are some additional components, such as irrigation systems, depending on climatic conditions (Castleton et al., 2010).

Green roofs can be divided into three categories (extensive, semi-intensive, and intensive) depending on maintenance, irrigation, plant community, substrate height, weight, cost, and use. As illustrated in Table 1 (IGRA, 2017).

Intensive roofs are heavier and more expensive compared to other types. Also, they require a higher level of maintenance. The extensive ones, because they are lighter in weight, have a shallower growth substrate and their maintenance cost is remarkably low (Coma et al., 2016).

Table 1. Classification of green roofs.

Criteria	Extensive Green Roof	Semi-intensive green roof	Intensive Green Roof
Maintenance	Low	Periodically	High
Irrigation	No	Periodically	Regularly
Plant community	Moss-Sedum, Herbs and Grasses	Grasses, herbs and shrubs	Lawn or perennial shrubs and trees
Substrate height	60-200 mm	120-250 mm	150-400mm; in underground garages, > 1000 mm
Weight	60-150 $kg.m^{-2}$	120-200 $kg.m^{-2}$	180-500 $kg.m^{-2}$
Cost	Low	Medium	High
Use	Ecological protection layer	Projected green roof	Park with garden

Benefits of Green Roofs

Green roofs are the best rainwater management practices in urban areas because the layers of vegetation and substrate can store a large amount of water (Chen et al., 2015). As a result, the chances of flooding in urban areas decrease.

Depending on the type of vegetation, evapotranspiration can be increased, as the growing medium absorbs a large amount of rainwater, which causes a reduction in runoff. The reduction in runoff depends on many factors, which include vegetation type, substrate thickness, type of drainage material, type of green roof (intensive or extensive), age of the green roof, rainfall intensity, and slope of the roof. However, the most important part is the green roof substrate, which must have high moisture retention, capable of storing more rainwater (Hashemi, Mahmud and Ashraf, 2015; Shafique, Kim and Rafiq, 2018).

In studies conducted on green roofs in Chongqing, China, researchers assessed the stormwater holding capacity in 19 rainfall events. Through this, the authors could observe that the green roof maintained the runoff at an average rate of 77.2%, indicating that these types of roofs are the solution for managing rainwater in urban areas (Zhang et al., 2015). Similar results were found by Razzaghmanesh and Beecham (2014), who observed that the use of green roofs maintained the flow at 65.7% in Manchester, UK.

In addition to controlling surface water runoff, the use of green roofs contributes to improving water quality (Liu, Li and Li, 2017). Berndtsson, Emilsson and Bengtsson (2006) reviewed several articles analyzing the water quality performance of green roofs and concluded that the percentage of heavy metals in urban runoff was significantly higher than runoff from green roof surfaces. Getter and Rowe (2008) also reviewed articles from different regions and found that green roofs can improve water quality.

The presence of green roofs provides thermal well-being to buildings, resulting in their cooling and, consequently, reducing energy costs (Getter et al., 2011). The vegetation and substrate of green roofs absorb less solar radiation when compared to other types of roofs, favoring, for example, the reduction of expenses used for cooling (Yan, 2011). That said, in studies carried out to analyze the energy consumption of the green roof in Shanghai, China, it could be seen that the energy savings during the day was around 20.9% and, at night, on average 15, 3% (Zhao and Xue, 2008).

Several studies report the ability of green roofs in urban areas to reduce the phenomenon of heat islands (Palla, Gnecco and Lanza, 2010; He et al., 2017; Shafique and Kim, 2017). He et al. (2017), in their research investigated the thermal performance of green roofs, proposing two new indices: insulation factor and comprehensive temperature regulation factor. From the analysis of the results, they found that the insulation factor had a small variation, while the comprehensive temperature regulation factor had a great variation in different seasons of the year. Therefore, the results of the comprehensive temperature regulation factor indicate that, in Shanghai City, the cooling effect of the green roof is stronger in summer than in winter. Furthermore, the results also indicated that the leaf area index, the reflectivity of the substrate layer, and the common roof are the main factors responsible for the change in temperature regulation.

Qin et al. (2013), when verifying the surface temperature of a green roof and a roof without vegetation, could observe that the green roof showed promising results in decreasing the surface temperature, compared to the roof without vegetation.

Sun et al. (2013) studied green roofs at two different locations (Tsinghua University, China, and Princeton University, United States) to analyze their surface temperature variation. Through the results, it was observed that the green roofs significantly reduced the surface temperature and heat losses in both locations. In Cuiabá, Mato Grosso, Rosseti, Nogueira and Nogueira (2013), verified a reduction of up to 0.75°C in air temperature and an increase of up to 12.3% in relative humidity in regions close to the prototype of a green roof about the farthest region, with the same morphological characteristics.

The use of green roofs also can capture dust particles from the air, favoring comfort for the population in urban areas (Shafique, Kim and Rafiq, 2018). Zhang et al. (1997) in their research showed that a 1000 m_2 green roof can capture approximately 160-220 kg of dust particles per year, resulting in an improved environment.

Trees are responsible for absorbing a large number of dust particles from the air (Chen et al., 2006). A study in China showed that tree species are responsible for capturing 87.0% of the dust in the air, 11.3% bushes and 1.7% lawns, proving that trees have a greater capacity to absorb these atmospheric pollutants (Zhao, Li and Yan, 2002).

Therefore, the use of green roofs classified as intensive, are the ones that can favor the reduction of these pollutants, considering that these roofs shelter large species, that is, arboreal species.

In addition, the use of green roofs provides social benefits, as they provide comfort to concrete constructions through the introduction of green spaces in urban areas, as well as creating opportunities for urban agriculture, being able to produce different vegetables, favoring the food production.

Whittinghill, Rowe and Cregg (2013) when working with tomatoes, green beans, cucumbers, peppers, basil, and chives for food production on green roofs in Michigan, United States, were able to prove that all crops, except pepper, produced enough yield and are very useful for the production of food from green roofs. The results also indicated that the proper selection of management and type of plant can ensure greater food production.

Carbon sequestration and green roof

Building green roofs may be one of the most important approaches to mitigating climate change, however, most studies on carbon sequestration have focused only on terrestrial ecosystems.

The type of substrate and the plant species adopted on the green roof has a great influence on the capacity for carbon sequestration (Getter et al., 2009), and may have a positive effect on mitigating climate change. The substrates used must present some physicochemical and biochemical requirements to ensure the good development of the plant, such as high water retention capacity, good aeration, low bulk density, and adequate drainage, which are some of them (Ondoño, Martínez-Sánchez and Moreno, 2016). In addition to the substrate, management practices can also affect net carbon sequestration (Whittinghill et al., 2014).

Agra et al. (2017), in their studies, evaluated the effect of plant-community composition on carbon fixation on green roofs in the semiarid region of the Mediterranean. In this study, they used a local Mediterranean species (*Sedum sediforme*) in comparison with other annual species, in a factorial design with the presence and absence of Sedum, crossed with the presence and absence of annuals. In the end, they found that the annual species reduced CO_2 concentrations, but only in the absence of Sedum. Thus, the Sedum species alone did not affect CO_2 concentrations. This emphasizes, in this study, the importance of integrating plots with annual plants into green roofs.

In works carried out by Getter et al. (2009), it was found that green roofs have a significant potential for carbon capture, both by biomass and by the substrate, presenting in this study sequestration of 375 g $C.m^{-2}$. However, when capturing and storing carbon, the size of the plant and the thickness of the substrate used must be taken into account.

Assessing carbon sequestration through studies using modeling in Hong Kong, China, Peng and Jim (2015) were able to observe that extensive and intensive green roofs can substantially reduce the concentration of atmospheric CO_2. Under the conditions of the then research, the authors observed that extensive and intensive green roofs were able to reduce the annual CO_2 emission by an amount of 7.4x104 and 1.3x105 tons of CO_2, respectively. Such concentrations indicated that the use of green roofs can satisfactorily help meet the targets for reductions in CO_2 emissions set by the Hong Kong government (between 0.8 and 1.4 million tons per year).

The ability to purify the air through plants has received increasing attention, mainly due to the degradation process that the environment has gone through. Thereby, Li et al. (2010), evaluated the effect of using a green roof on atmospheric CO_2 concentrations, as a way to assess the benefits of these in urban areas. Through this, the authors observed that, for the climatic conditions of Hong Kong, plants can reduce atmospheric CO_2 concentrations, mainly during the day, and that CO_2 emission rates are reduced at night. Furthermore, the effectiveness of the green roof in terms of carbon sequestration will depend on factors such as the type of plant placed on the green roof, the position of the green roof, and the airflow of the environment.

Conclusion

Even though it is not such a recent practice, discoveries related to the benefits of using plants on buildings are growing. The use of green roofs has shown to be a promising alternative for the thermal comfort of the interior of buildings and as a system capable of sequestering atmospheric carbon. On the other hand, it is noteworthy that most scientific investigations related to carbon dynamics are carried out in other countries and have involved natural, agricultural, urban, and community forests, with few studies on carbon sequestration by green roofs at a national level.

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