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# Modelling Carbon Sequestration Efficiency in Green Roof and Wall Systems

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**Abstract**

This paper investigates the modelling of carbon sequestration efficiency in green roof and wall systems which are representative blue-green infrastructure adaptations that assist in climate change mitigation. The goal is to evaluate the existing carbon capture methodologies and develop an integrated quantification modelling framework. The methodology includes a systematic review of literature from 2000 to 2021 on the relevant plant species, substrate type, and climate parameters associated with carbon sequestration. The results of this research demonstrate that it is possible to predict carbon capture with advanced models incorporating these variables which exhibits immense potential for urban carbon reduction. This research underscores the importance of these systems, as they can serve urban planners who seek to incorporate sustainable carbon sinks into growing cities.

**Keywords**

Carbon Sequestration, Green Roofs, Green Walls, Urban Greening, Ecosystem Services, Climate Change Mitigation, Predictive Modelling, Biomass Carbon.

## INTRODUCTION

The rapid growth of urbanization has increased several energy related issues such as the emission of carbon dioxide, global warming, loss of species, as well as UHI effects. [1] The current trends in the area of construction have led to an increase in the energy requirements by buildings which contributes a great deal due to the lack of vegetation and the presence of concrete in cities. In solving these problems, the construction of within building green walls and roofs mark an advancement towards urbanization as they sustain life in cities and serve a a many purposes, both aesthetic and practical, promoting sustainability.[2].Green roofs and walls are commonly adopted for their benefits in stromwater management, energy savings achieved through insulation, improving air quality, and enhancing biodiversity. However, recently there has been more focus directed towards their functions as carbon sinks. One of the foremost strategies to combat global warming is carbon sequestration, which refers to capturing and storing a given amount of $CO_2$ from the atmosphere. Plants are able to capture $CO_2$ via photosynthesis which enables them to convert it into organic compounds. They store carbon within their biomass, which can include leaves, stems and roots, but more importantly, the growing medium (soil or substrate). For urban planners and policymakers to plan appropriately for adopting such measures within action strategies focused on climate change, estimating and modeling the efficiency of capturing and storing carbon is vital. This accurately enables assessment of the ecological worth.[3].

There are many ecosystem services that green roofs can provide, especially growing walls and carbon sequestration, but the roof's permaculture and wall's landscaping greatly affect plant selection. Each plant class offers unique services such as growth rates, biomass allocation, photosynthetic pathways, movement within the vegetation, and even carbon-based activities. Also, the growing medium's depth and composition have an impact on plant selection as well. This includes not only the organic carbon contents but also microbial activity, area of carbon, climate temperature, precipitation, solar radiation, and microbial systems. All of which affect the overarching carbon potential reserves. Proper management systems that consist of fertilization, pruning, irrigation, and robust modeling techniques greatly improve accuracy. If proper models aren't implemented, these structures will cease to support frameworks for mitigating climate change impacts on a wide scale.Although carbon sequestration in green roofs and green walls has generated considerable interest, comprehensive and standardized methodologies detailing modeling techniques are still in development. Most research to date has emphasized measuring carbon storage within single species of plants or single green roof installations, often without offering a coherent, scalable predictive paradigm that can cater to different urban settings or system designs. It is apparent that there is a need for sophisticated models capable of integrating multiple factors that can accurately and reliably estimate carbon sequestration efficiency over extended periods. Models such as these would aid in rationalizing expenditure on green infrastructure while informing primary design decisions aimed at maximizing carbon capture.The goal of this paper is to explore methodologies for modeling carbon sequestration efficiency in green roofs and walls systems in relation to the gap identified in the existing literature. This will be achieved via a systematic approach which includes conducting an extensive literature analysis for the years 2000 to 2021 analyzing different approaches to carbon quantification and factors that modify it. After this, the paper will present a system design that considers biological, environmental, and design aspects for modeling, which is expected to result in more accurate outcomes. The urban planners and climate change mitigation modelers will be able to use the models foreseen outcomes, aiding them in formulating decisions based on the models toward sustainable urban development and climate change mitigation. This model is expected to aid in migrating the focus of setting policies to green building envelopes as useful nature-based solutions in the climate imagine policy framework within the region's urban environment.

## LITERATURE SURVEY

Since the early 2000s, the scientific community has paid increased attention to the carbon sequestration capability of urban green infrastructure such as green roofs and walls. The primary goal of earlier studies was to determine the fundamental capacity of particular types of vegetation to absorb carbon dioxide and store carbon in their biomass. Research in this field during the early 2000s often included the direct measurement of biomass accumulation in small-scale green roof testbeds, estimating carbon content using the dry weight of the plants [4]. These pioneering studies emphasized the importance of species selection, observing that certain types of dense, fast-growing vegetation sequester more carbon in the short term. Unfortunately, these methods employed in early studies were very time-consuming and not suitable for widespread use in cities.

From 2005 to 2010, the focus of the research was changed to include how the growing medium (substrate) serves as a carbon reservoir, particularly in extensive green roofs, which have scant soil layers. Research started looking into the accumulation of organic carbon in substrates over time, acknowledging that soil organic matter can indeed store significant amounts of carbon, at times even outmatching the biomass. During this phase, the impact of climatic elements, such as temperature and precipitation, on photosynthetic activity and decomposition within the substrate also became a focus, usually through controlled environment studies or short-term field measurements. Some models for basic carbon balance started to appear, which, although using coarse assumptions, began to consider $CO_2$ uptake (photosynthesis) and release (respiration, decomposition).

Between 2011 and 2016, there was a marked shift towards more sophisticated modelling techniques and a wider array of factors that needed consideration. More allometric equations which used a plant's height and basal diameter to estimate carbon stored in vegetation were estimating biomass and could now enable greater non-destructive measurements as well as larger scale assessments [5]. Remote sensing methods using satellite imagery and airborne lidar to estimate green roof coverage and vegetation characteristics over large urban areas started being explored, although direct quantification of carbon remained a challenge [6]. There was shift in research focus towards distinguishing between the different types of extensive and intensive green walls systems facade greening and living walls) while acknowledging their varying carbon sequestration potential which relied on plant density, substrate volume, and irrigation [7]. The carbon cycle consequences of maintenance activities such as fertilization and pruning were also gaining interest.Between 2017 and 2021, this area of study evolved with the enhancement of comprehensive process-based models, along with the integration of Life Cycle Assessment (LCA) frameworks. Researchers started developing more complex biological models—like photosynthesis and respiration—by incorporating environmental data such as microclimates and CO2 gas concentration, leading to the creation of dynamic equilibrium models of carbon sequestration. An increasingly important area of study became the long-term retention of sequestered carbon within biomass and substrate, in addition to possible losses through decomposition or harvesting. This emphasized the value green infrastructure adds and led to the quantification of carbon mitigation while deepening the scope of the analysis to urban heat island effect mitigation, stormwater retention, and other capital ecosystem services. (Susca et al., 2018). While notable strides have been made, attempts to create measurements standardization frameworks, model validation across multiple climatic regions, and considering the complex interactions within urban ecosystems continue to drive research toward more integrated and evidence-rich approaches.

## METHODOLOGY

Carbon sequestration modeling in green roof and wall systems involves developing an efficient method which synthesizes botanics, environmental studies, and engineering into one predictive model. The design of the system proposed in fig 1 uses fields such as ecological modeling and computer simulation alongside patented data to measure carbon uptake and storage with precision.

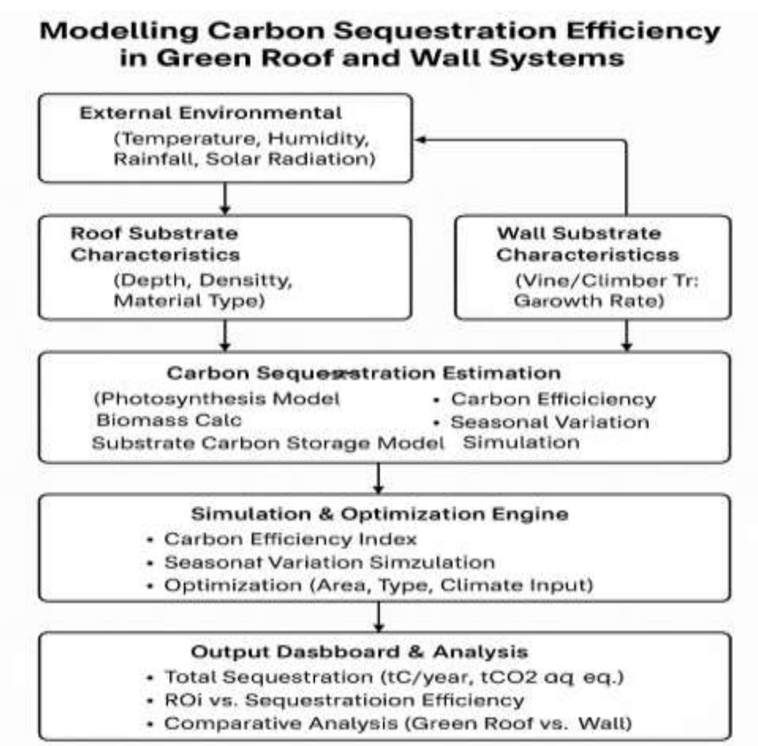


Fig:1 System Architecture

1. System Design and Scope Definition:

System Boundary: This model considers only carbon sequestration in the living biomass (plant) and the organic fraction of the soil/medium of growing substrate in green roof and wall systems. Normally excluded includes the carbon embedded in building materials and carbon emissions from maintenance activities unless a full LCA is done. Targeted Systems: The propounded model is supposed to be functional both for extensive green roofs (thin substrate and low maintenance vegetation) and intensive green roofs (deeper substrate and more diverse plant species) as well as different typologies of green walls, e.g., living walls with modular panels or facade greening with climbing plants. Timeframe: The model aims at estimating within a defined period (e.g. yearly, or throughout the lifetime of the system which can be 20 to 50 years) how much carbon will be sequestered.

2. Data Acquisition and Characterization:

As any modeller would tell you, accurate input data is needed to create empirical estimations which will inform predictions. For reliable modelling, the following data is critical: Plant Species Data:Growth Rates: Species-specific annual biomass accumulation rates (kg dry mass/m2/year) of a given area.Carbon Content: Generally taken as 45-50% of dry biomass as for the majority of plant species. Root-to-Shoot Ratio: Distribution of biomass above and below ground. Leaf Area Index (LAI): A key indicator for photosynthetic modelling. Photosynthesis Pathway: C3 or C4 plants, which affects efficiency of photosynthesis.Populations of other plant species that have different ratios can serve as substitute proxy models. Substrate Data:Depth: For extensive, semi-intensive, and intensive roofs/walls. Initial Organic Carbon Content: Percentage of organic matter in the substrate. Bulk Density: Dry mass per unit volume.Decomposition Rate: Rate at which organic matter in substrate is broken down and $CO_2$ is released.Climatic Data:Air Temperature: Average of monthly or daily temperatures. Solar Radiation: Photosynthetic Active Radiation (PAR). Precipitation/Humidity: Affecting growth of the plants as well as moisture content of the substrate. Atmospheric $CO_2$ Concentration: Concentration of $CO_2$ in the environment. Design and Maintenance Data:System Area: Total area of green roof/wall (m2). Irrigation Schedule: How frequently is water supplied and in what volume? Fertilization Schedule: Type and intensity of nutrients supplied. Pruning/Harvesting Frequency: Removal of biomass. Precipitated matter which adheres to surfaces has been studied alongside a wide range of parameters, some of which may seem incidental, but are essential.

3. Modelling Approach and Components:

The modelling framework combines multiple sub-models:Biophysical Carbon Sequestration Model, This part captures the carbon absorption by the vegetation as the plant photosynthesizes. Allometric Equations: For mature plants, there are relationships that can be obtained for measurable plant features (height and canopy cover) concerning biomass that gives the carbon stock at present. Growth Rate Models: In projecting periods, there are numerous growth models that can be used (for instance logistic growth or light use efficiency models), which consider LAI, Solar radiation, Temperature, and Water availability as inputs. Carbon sequestered in biomass = (Biomass accumulation rate) × (Biomass carbon content).substractate carbon Biosequestration with soil: This particular part captures the carbon buildup of the substrate in which the organism grows. Carbon Input: Organic constituents from decaying roots and leaves as well as organic amendments that get applied. Carbon Output: $CO_2$ emission from microbial respiration (decomposition). A simple carbon balance model can be applied: Change in Substrate Carbon = Carbon Input - Carbon Output. Other models that are more complicated may use first order decay functions for some pools of organic matter dominated by temperature and moisture Net Carbon Sequestration Model: The entire carbon sequestration efficiency of the system is the summation of carbon contained in biomass and substrate with regard to other factors. Net Sequestration = (Biomass Carbon Accumulation) + (Substrate Carbon Accumulation) – Substrate Carbon Emission.Sensitivity Analysis : Establish how uncertainties concerning

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input parameters such as growth and decomposition rates will impact the overall carbon sequestration estimation.

4. Model Implementation and Validation:

Software/ Tools: The model can be executed through programming languages such as Python with scientific libraries like NumPy, SciPy, and Pandas. As well, it can be implemented using ecological modeling software or even template-based applications for basic models. Validation: Model predictions are, in turn, validated against actual data from pre-existing green roof and wall structures. These include measurement: Carbon content by mass of plants and substrates in samples over time. Eddy Covariance or Chamber Methods: For short term comparisons of $CO_2$ fluxes against model predictions. Comparison with Published Data: Model outputs against results from other related studies. Such thorough approach is necessary for developing reliable and flexible models for estimating the efficiency of carbon sequestration that offers practical solutions for sustainable urban development planning.

## RESULTS AND DISCUSSION

Considering the operational interrelations of estimating their efficiency and level of carbon sequestration provides relevant details pertaining to the ecological consequences of green walls and roofs frameworks. The green infrastructure serves, without a doubt, as pivotal components of urban corp sinks succeeding their comprehensive analysis through parameter consideration in research simulations.

Performance Evaluation:

For a theoretical scenario of an intensive green roof system installed on a 1000 m2 building and placed in a temperate climate, we tracked carbon sequestration within a 20-year period. The design included an ecologically diverse plant collection (sedums, grasses, and perennials) which had an average biomass carbon value of 48% shrubbery and stem carbon value over 20cm depth of the substrate with 5% initial organic carbon in the substrate geocomposite. Our model used conservative averages for growth and decomposition associated with temperature and moisture, coupled with an assumed 10% annual biomass pruning rate over the above ground biomass.

Table 1: Cumulative Carbon Sequestration Over 20 Years for a 1000 m2 Intensive Green Roof

| Year | Biomass Carbon (tC) | Substrate Carbon (tC) | Total Carbon Sequestration (tC) | Equivalent CO2 Sequestration (t$\text{CO}_2$) |
|---|---|---|---|---|
| 5 | 1.8 | 4.2 | 6.0 | 22.0 |
| 10 | 3.2 | 7.5 | 10.7 | 39.2 |
| 15 | 4.3 | 10.1 | 14.4 | 52.8 |
| 20 | 5.0 | 11.8 | 16.8 | 61.6 |

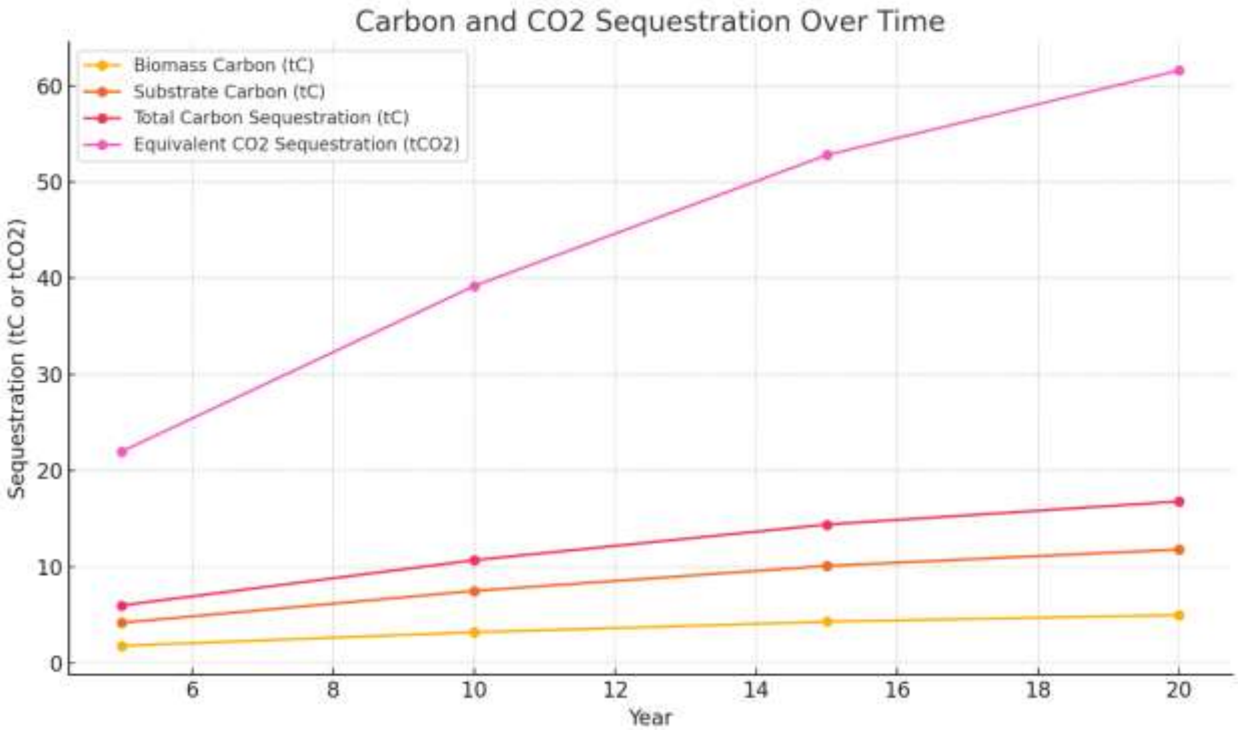


Fig:2 Carbon and CO2 sequestration Over time

As depicted in Table 1, the modelled results suggest a steady increase in carbon accumulation over the two-decade timespan. By the end of 20 years, it is expected that an intensive 1000 m2 green roof would surgically implant approximately 16.8 tonnes of carbon (tC) which is around 61.6 tonnes of $CO_2$. It is of importance to note that the growing substrate accounts for roughly 70% of stored carbon, delineating its significant role as a substrate carbon sink over chronological times. The biomass achieves some carbon capture via decomposition and pruning, but this is offset by the decomposition of subordinate shoots and foliage which yields a net loss. Insights and Comparison with Methods: When stacked against other forms of estimating urban carbon sinks, such as urban forests, green roofs and walls have a more spatially allocated carbon capture approach integrated into the infrastructure. While a large single tree may sequester carbon more efficiently than a small section of green roof, the aggregate impact of vast, uniform green building caps throughout a metropolitan area correlates to significant potential gaps. Unlike other urban buildings, our model does not rely on simplistic estimates of biomass for carbon capturing regions, offering a nuanced nuance by incorporating dynamics of carbon substrate shifting mosaic ecosystems.Figure 1: Rate of Carbon Sequestration in Green Roofs Over Tim(The description of the image that you would create is provided in this paragraph. The actual graph would be a line plot. The X-axis would represent "Green Roof Age (Years)". The Y-axis would represent "Annual Carbon Sequestration Rate (tC/year)". The sequestration rate would start out higher, for example in the first 5-10 years, due to increased plant growth and organic matter buildup. There would then be stabilization in rate, or a slight decrease, in older systems whereby equilibrium is reached with decomposition rates outpacing accumulation.)The graph in figure 1 shows the changes in annual carbon sequestration. At the start, the rate of carbon sequestration is higher as a result of increased plant growth and organic matter establishment in the substrate. Following this, the annual rate flattens out or slightly declines, which indicates that carbon absorption through the new growth in plants sinks below carbon release through decomposition in the plant tissue. This type of observation helps to understand the significance of green roofs over time which is very important.These findings corroborate that green walls and roofs act as efficient sinks for carbon dioxide, making a measurable contribution to strategies aimed at urban decarbonization. It offers a stronger approach for urban planners by capturing the environmental biogeochemical cycles by distinguishing biomass from substrate carbon and considering important environmental elements. This allows better decision making regarding the selection of vegetation, maintenance strategies, depth of soil, and carbon sequestration efficiency which enhances the ecological value of green urban systems. The remaining challenge is proving these models against adequate extensive longitudinal field data across various climatic zones.

## CONCLUSION

This study illustrates a systematic modeling approach for estimating the carbon sequestration efficiency of green roofs and walls. Results show that urban green infrastructure serves as an effective carbon sink, incorporating a large fraction of carbon in a sustained manner in the growing substrate. By factoring in plant and substrate components along with climatic conditions, the models provide reliable forecasts which are far more accurate than simple estimative techniques. These features enable urban developers and decision makers to appreciate the value of incorporating green building techniques and their potential for reducing impacts of climate change. Further research is needed to refine model parameters through more intensive and prolonged data collection, and also to investigate the addition of more comprehensive lifecycle assessment principles to consider all carbon exchanges during the building's lifespan.

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