

Challenges and solutions for achieving carbon neutrality through urban green infrastructure in China's future cities

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ABSTRACT

China has committed to achieving carbon neutrality by the 2060s. In this context, urban green infrastructure (UGI) is increasingly recognised as a nature-based solution with a significant potential for climate change mitigation and adaptation, while also contributing to the broader achievement of sustainable development goals. Although the carbon reduction potential of UGI is been widely acknowledged, several critical gaps remain in understanding its mitigation mechanisms, the integration with carbon qualification methods, the identification of influential factors, and the evaluation of UGI's potential as a mainstream strategy for achieving carbon neutrality. This study systematically reviews evidence from 464 global publications, including 85 focused specifically on China, to address these gaps. We categorise UGI's carbon mitigation mechanisms and align them with the corresponding carbon quantification methods, highlighting the strengths and limitations of each across three primary pathways: carbon sequestration, thermal regulation, and urban agriculture. Furthermore, we identify critical factors influencing carbon mitigation outcomes and assess the methodological trade-offs inherent in the different qualification approaches. The study also explores the current landscape of UGI-related carbon initiatives at multiple governance levels in China and offers recommendations for policy development at national, regional, and local scales. By synthesising scientific evidence with policy analysis, this research provides a foundation for leveraging UGI as an integrated and scalable strategy to support the achievement of carbon neutrality.

1. Introduction

The Paris Agreement aims to limit the global average surface temperature increase [1]. In line with this goal, and in recognition of the growing international consensus that achieving carbon neutrality is essential for addressing climate change and mitigating global warming, a total of 151 countries – accounting for approximately 88% of global greenhouse gas (GHG) emissions – had set carbon neutrality targets by September 2023 [2,3]. Most of these governmental commitments outline long-term emission reduction objectives to be achieved by the mid-21st century [4].

While national-level targets provide strategic direction, cities - home to over half of the global population and responsible for more than 70% of GHG emissions - represent critical frontlines in climate action. Urban areas not only contribute significantly to global emissions but also serve as hubs for innovation, infrastructure transformation, and policy

experimentation. In this context, urban planning plays a pivotal role in facilitating low-carbon development pathways [5,6]. Among various urban strategies, urban green infrastructure (UGI) has gained increasing recognition for its potential to integrate carbon mitigation, sequestration, and climate adaptation within a unified spatial and policy framework [7,8]. Consequently, UGI is widely acknowledged as a key strategy for cities striving towards carbon neutrality, with some envisioning it as central to urban decarbonisation by 2030 ('Nature-based solutions can pave the way to carbon-neutral cities in 2030', [9]).

UGI refers to interconnected networks of natural, semi-natural, and constructed ecological systems within and around urban environments, functioning at multiple spatial scales [10]. Designed to provide a wide range of environmental services [11,12], UGI incorporates features such as green roofs, vertical gardens, urban parks, forests, waterways, permeable pavements, and urban farms [13–15]. Acknowledged as a resilient carbon sequestration subsystem, UGI plays a pivotal role in

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regulating urban carbon cycles [6]. Empirical evidence from 35 Chinese cities indicates a combined carbon storage capacity of approximately 18.7 million tonnes [16]. In Beijing alone, urban green spaces absorb an estimated 8.99 million tonnes of CO₂ annually [17], while in Hangzhou, a total of 238.7 tons of carbon were sequestered by natural means [18].

Furthermore, UGI is estimated to offset approximately 0.33% of carbon emissions from fossil fuel combustion, highlighting its potential significant contribution to carbon neutrality, particularly if supported by appropriate policies [13]. Despite growing recognition of UGI's role in sustainable urban development and carbon storage [19], most existing research has primarily focused on the carbon reduction impacts of various forms of UGI without thoroughly exploring the underlying mechanisms [20–23]. As urban planners and policymakers increasingly focus on UGI construction and planning [24,25], significant gaps remain in developing comprehensive strategies for leveraging UGI as a primary tool for carbon reduction.

China's trajectory exemplifies the urgency and complexity of this challenge. In 1990, China contributed only 5% of global CO₂ emissions [26]. However, rapid economic expansion following the reform and opening-up period has positioned China as the world's largest carbon emitter [27,28]. In response, China has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by the 2060s [29,30], making its progress pivotal to the achievement of global climate goals.

Understanding how Chinese cities deploy UGI to reduce emissions and enhance carbon sequestration is thus crucial – not only for China's domestic climate commitments but also offering transferrable insights to other rapidly urbanising nations [31]. While China's ongoing urbanisation poses significant challenges for embedding UGI within urban planning and governance systems, it also presents unprecedented opportunities for innovation and large-scale implementation. Notably, data indicates that the development of UGI in China accelerated significantly between 2005 and 2020 [32], providing a solid empirical foundation for this study, which aims to conduct a systematic review and comprehensive analysis of UGI's carbon mitigation potential.

This review aims to synthesise existing evidence on the potential and pathways of UGI for achieving carbon neutrality, investigate the reasons behind the variability in UGI's carbon reduction benefits, and advocate for the mainstreaming of UGI as a central tool in carbon neutrality efforts. To enhance UGI's effectiveness and promote its widespread adoption, it is crucial to understand the fundamental carbon reduction mechanisms of UGI, identify the factors contributing to variations in its carbon reduction benefits, and determine actionable steps to advance UGI utilisation in China towards carbon neutrality. Specifically, this review will:

- (i) classify the fundamental carbon reduction mechanisms of UGI;
- (ii) conduct a methodological comparison across key carbon reduction pathways to evaluate their strengths and limitations;
- (iii) examine factors contributing to variations in UGI's carbon reduction benefits; and
- (iv) recommend actions to promote the utilisation of UGI in China in support of its carbon neutrality goals.

The contribution of this study lies in providing a structured, multi-scalar framework for UGI policy integration, clarifying how technical mechanisms, spatial patterns, and governance levels interact to affect UGI's climate potential, and offering targeted recommendations to support the strategic mainstreaming of UGI in carbon-neutral urban transitions.

2. Materials and methods

2.1. Web of science keywords searching

This study employs a combination of bibliometric analysis with a narrative literature review. A systematic literature search was

conducted using the Web of Science database on January 19, 2024, to identify relevant publications on UGI and carbon. The search strategy was adapted from the approaches used by Fang et al. [33] and Zhao et al. [34].

The search terms applied were: TS = (“urban*” OR “cit*”) AND TS = (“Green infrastructure*”) AND TS = (“carbon”). The search was limited to English-language publications from 1990 to 2023. This initial query yielded a total of 2,058 articles.

2.2. Article inclusion criteria

To assess the quality of the retrieved articles, titles and abstracts were independently reviewed, and duplicates were removed. Full-text versions were obtained for articles that met the following inclusion criteria:

- (1) The study focused exclusively on urban areas (excluding peri-urban and rural settings).
- (2) The paper addressed UGI in relation to carbon sequestration, carbon sinks, carbon reduction, and/or carbon storage.
- (3) The source was a peer-reviewed journal article or conference paper.

Papers that only made general references to the carbon sink benefits of UGI without providing in-depth analysis were excluded for further analysis. Following the screening process, 464 articles remained. The geographic scope was then limited to studies conducted in China, resulting in 85 articles for detailed review in the subsequent analysis (Fig. 1).

2.3. The foci of carbon research in UGI

To better understand the current research landscape and identify knowledge gaps at the intersection of UGI and carbon reduction, this section presents a bibliometric analysis of both international and China-focused literature. The aim is to explore how research in this field has evolved over time, identify key themes, and highlight potential directions for future investigations, especially in the context of China's growing academic contributions.

Although the term “green infrastructure” (GI) was initially introduced in 1995 [35,36], it was not until 2010 that Ding et al [37] made one of the earliest efforts to explicitly link GI to urban green space and the concept of “low carbon”. Since then, a total of 464 papers on the integration of UGI and carbon reduction have been recorded (up to and including 2023; Web of Science). The number of studies began to increase significantly after 2015 (Fig. 2).

In 2020, following China's commitment to its “3060” targets – peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 [30] – research activity in this area accelerated. By the end of 2023, China had become a leading contributor to UGI and carbon research, accounting for over 19% of global publications (Web of Science). With 85 papers, China ranked first, followed by the United States, the United Kingdom, and Italy. This growing body of work suggests that China is beginning to play a pivotal role in advancing knowledge on UGI's contribution to carbon reduction and may significantly influence the future research agenda.

We employed VOSviewer software (Leiden University, The Netherlands) to generate a visual overview of current research on UGI and carbon in China. The software extracted frequently occurring academic terms from 464 papers and analysed their frequency and co-occurrence within individual papers. Keyword frequency and co-occurrence patterns were used to identify thematic foci within the literature. In the resulting network map (Fig. 3), the proximity between terms reflects the frequency of their co-occurrence, the size of each term represents its overall frequency, and the colour indicates the temporal distribution of the term's use over time.

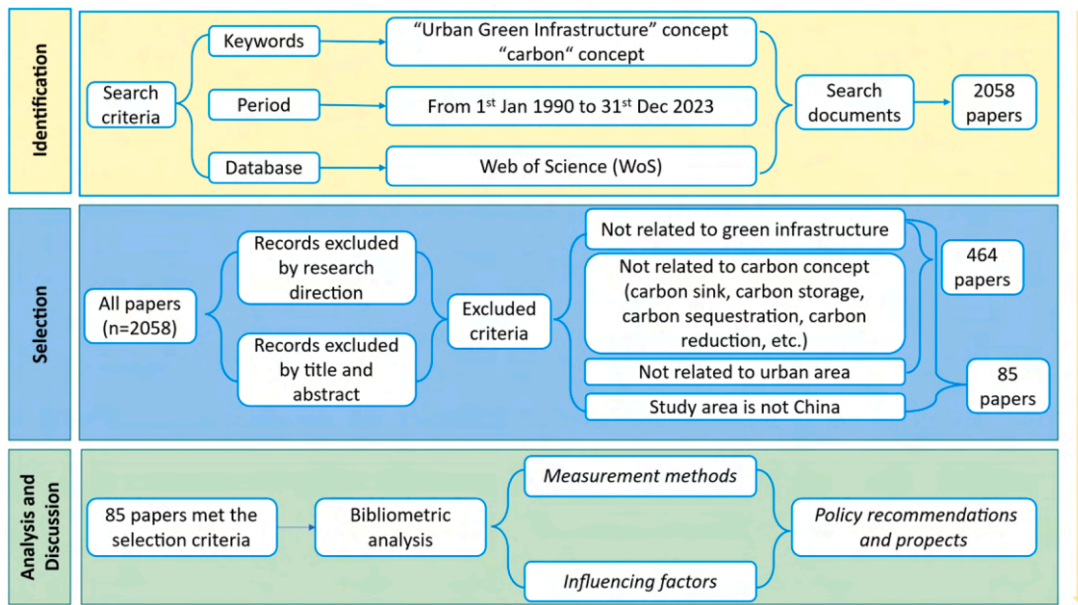


Fig. 1. Flowchart of the literature-screening process and research framework. Source: Authors.

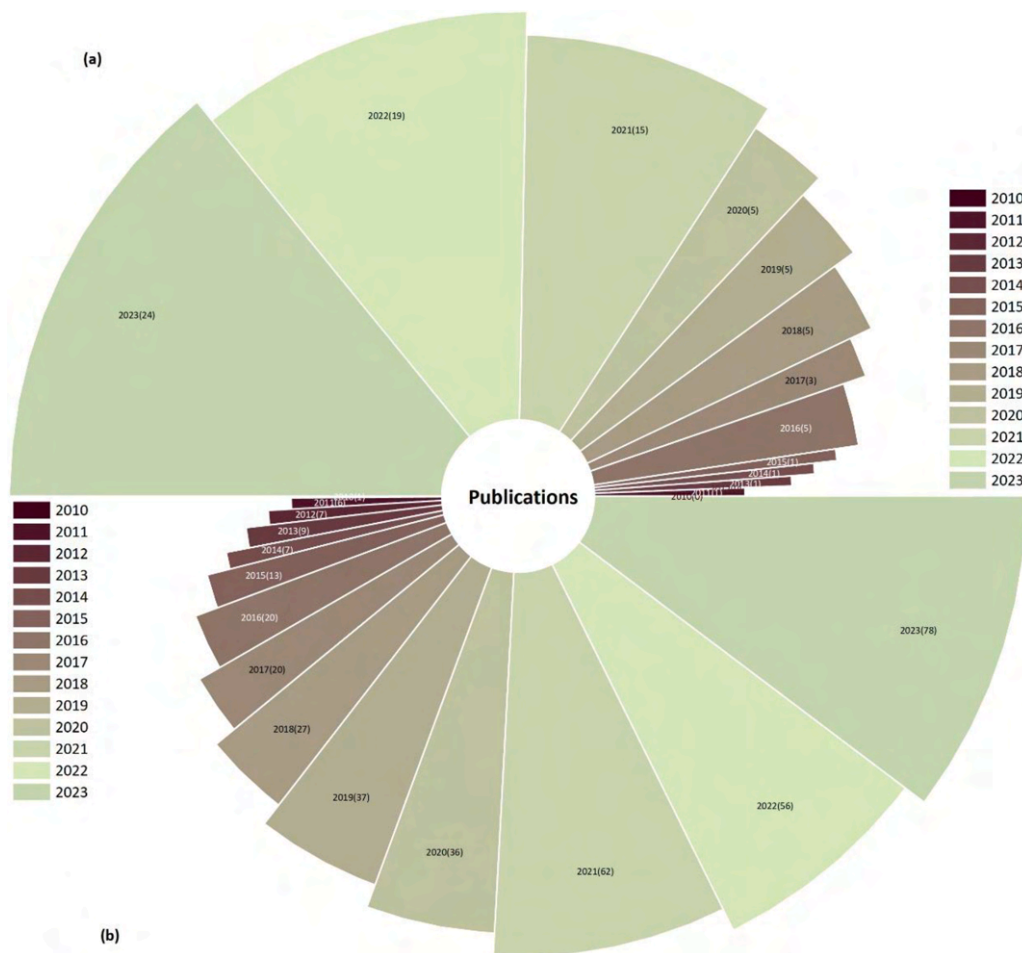


Fig. 2. Number of publications on UGI and carbon in China and globally from 2010 to 2023. (a) Number of publications focusing on China, and (b) number of publications on this research topic globally, excluding China. Source: Authors.

The analysis shows that initially, the term “ecosystem service” dominated the research landscape. While terms such as “urban forest”, “green roof”, and “urban green space” are present, they appear to have received comparatively limited attention. Notably, terms such as ‘policy’, ‘UGI’, ‘NBS’ and ‘carbon’, are more recent, as indicated by their colour coding, suggesting a growing academic interest in these areas.

However, the sparse connections among these keywords highlight a fragmented research landscape, with limited integration of themes such as policy and UGI. This finding supports calls for further research on the policy dimensions of UGI [38], which could facilitate the mainstreaming of UGI as a strategy for advancing carbon neutrality.

3. UGI's contributions to carbon neutrality

Carbon emissions are predominantly concentrated in the electricity, construction, and agriculture sectors [39]. An overview of UGI's contributions to carbon reduction reveals that it reduces carbon emissions or enhances carbon sinks through three primary mechanisms: carbon sequestration [40,41], thermal process regulation and building energy savings [23,42], and urban agricultural systems [18]. Consequently, we classified UGI into three systems (Fig. 4).

3.1. Mechanisms and empirical evidence of UGI's carbon mitigation effects

Carbon sequestration is a direct and fundamental method for reducing UGI-related carbon emissions and enhancing carbon sinks, playing a pivotal role in achieving carbon neutrality [42]. As the primary contributor to the ecological service benefits of UGI, carbon sequestration accounts for 69.34% to 73.76% of the total value [43]. Through photosynthesis, plants convert atmospheric CO₂ into oxygen [44], storing it as organic matter in vegetation and soil, thereby facilitating long-term carbon capture [45]. This process involves critical exchanges of CO₂ between UGI and the atmosphere, primarily through photosynthesis [46] and respiration [42]. Accumulated organic matter in vegetation acts as a vital carbon sink [47]. The effectiveness of this mechanism is reflected in multiple empirical studies. For example, Liu et al. [48] contended that UGI facilities in the Guangdong-Hong Kong-Macao Greater Bay Area have resulted in a reduction of 193.6 million tonnes of carbon emissions. Wu et al. [49] found that large-scale vegetation restoration on the Loess Plateau enhanced the total carbon sequestration on the Loess Plateau by 12 Tg C over 15 years. In Beijing, the annual carbon storage in urban forests in built-up areas amounts to 1,114,298.23 tons, while the gross carbon sequestration is 81,568.30 tons [50].

Among the most common UGI facilities, urban parks exhibit promising potential for delivering carbon reduction benefits. For instance, at China's Green Expo Park in Zhengzhou, the average carbon storage density is 40.63 kg·m⁻² and the carbon sequestration density is 2.65 kg·m⁻²·yr⁻¹ [51]. The average daily carbon sequestration efficiency of urban parks in Beijing is 8.72 g C/m² [52]. Urban parks in the Yangtze River Economic Belt can offset 5.37% of daily fossil fuel emissions [53], while UGI in Xi'an offsets 3.6% of the metropolitan area's fossil fuel carbon emissions [21].

Additionally, the vegetation canopy within UGI intercepts some of the heat flux and absorbs solar radiation, reducing urban surface temperatures [42,54]. This decrease in radiation not only lowers energy demands for cooling but also reduces anthropogenic heat sources, consequently diminishing carbon emissions [54]. For instance, in the Hong Kong-Macao Greater Bay Area, indirect carbon reduction due to climate regulation totalled 185.1 million tonnes in 2022, representing 29.5% of the area's total emissions. Moreover, increasing the forest and grass area ratio to 90% can reduce carbon emissions by 12% to 21% through the cooling effect, potentially enhancing carbon sequestration by up to 24,135 tons [55]. In addition to its inherent carbon storage and sequestration capacity, a portion of UGI's emission reduction potential is

attributable to the energy-saving benefits of its cooling effect.

For example, the construction of China's National Demonstration Eco-Industrial Park has reduced the city's carbon emissions by 3.08%, primarily by improving energy utilisation efficiency. This practice has also caused a significant spatial spillover effect, leading to carbon emission reductions within 450 km of neighbouring cities [56]. The annual carbon reduction from green roofs of a building in Nanjing can reach 4,355.6 g CO₂·m⁻², with a direct emission reduction of 46.6 g CO₂·m⁻² from vegetation's photosynthesis and an indirect emission reduction of 4,309 g CO₂·m⁻² from its cooling effect. Green roofs in Japan can reduce CO₂ by up to 1,889 kg CO₂·m⁻² per year due to energy savings [57].

UGI can also reduce CO₂ concentrations [58]. In Hong Kong, green roofs can reduce CO₂ concentrations in the surrounding area by nearly 2% [59]. Urban farms or home gardens contribute to a shift towards a low-carbon diet, reducing the carbon footprint from transportation, with an annual reduction of up to 205.1 kg of CO₂ per person [60].

Urban agriculture, which involves cultivating crops and raising animals in urban and peri-urban areas [61], is multifunctional, with environmental benefits being one of its key functions [18]. Urban agriculture can effectively reduce greenhouse gas emissions through carbon sequestration and provide significant economic value [18,62]. Additionally, it minimizes the carbon footprint associated with the transportation of food products [63] and supports a shift towards low-carbon dietary choices [60].

3.2. Comparative analysis of UGI carbon benefits

To quantitatively assess the variability in the carbon mitigation potential of UGI, we conducted a comparative analysis based on UGI type, climate zone, and city size. The results reveal significant differences in sequestration capacity across contexts, particularly for urban parks, whose performance varies widely with climatic and spatial conditions.

In humid subtropical zones, UGI types such as urban parks and green roofs consistently exhibit strong carbon mitigation outcomes across cities of varying size. For instance, in large cities like Wuhan and Nanjing, urban parks can account for up to 73.76% of local CO₂ storage, while green roofs show high sequestration potential ranging from 4.36 to 9.35 kg·m⁻²·yr [43,64,65]. In megacities like Shanghai, urban agriculture systems further enhance mitigation potential, achieving emission reductions of up to 9.6×10⁸ kg CO₂ equivalent, reflecting the scale-dependent amplification of UGI carbon benefits [63]. Similarly, urban parks within the Yangtze River Economic Belt have been shown to offset up to 5.37% of daily fossil fuel emissions [53].

Green roofs also exhibit notable regional variation. In humid cities like Nanjing and Wuxi, total CO₂ reductions – including both direct and indirect effects – can reach up to 1,889 kg CO₂/m²·yr [57]. In Chengdu, green roof designs with specific vegetation types achieved sequestration rates of 7.03 kg C/m²·yr [22]. These differences reflect the compounded effects of vegetation selection, local energy demands, and climatic responsiveness. Moreover, while mega cities such as Beijing and Guangzhou demonstrate greater total carbon reductions due to larger-scale UGI deployment and higher baseline emissions, smaller cities often achieve greater efficiency in carbon sequestration per unit area, despite having a lower aggregate impact.

Table 1 synthesizes representative empirical studies supporting this comparative evaluation. Overall, the findings underscore the importance of climate- and scale- sensitive UGI planning to optimise carbon mitigation benefits.

4. UGI's carbon reduction benefits and quantification methods

Previous studies examining carbon within the three UGI systems have not identified system-specific carbon quantification methods. Instead, most research relies on general modelling approaches. Commonly used tools include i-Tree Eco [69,50,70] and the InVEST

Table 1
Summary of research studies regarding the carbon emission mitigation by UGI.

UGI facility	Location	City size	Climate zone	Mitigation effect statement	Study
UGI	35 cities in China	Varied	Varied	UGI in 35 cities in China acts to offset carbon emissions by storing a total of 18.7 million tons of carbon.	[13]
UGI	Guangdong-Hong Kong-Macao Greater Bay Area, China	Mega City	Humid Subtropical	In 2022, UGI's carbon reductions reached a total of 193.6 million tons.	[48]
Vegetation restoration	The Loess Plateau, China	Varied	Temperate semi-arid	Total carbon sequestration was enhanced by 12 Tg C in 15 years following large-scale vegetation restoration.	[49]
Urban Forest	Beijing, China	Mega City	Warm temperate semi-humid	The annual carbon storage of urban forests in Beijing's built-up areas is 1,114,298.23 tons, and the gross carbon sequestration is 81,568.30 tons.	[50]
Urban parks	Wuhan, China	Large City	Humid subtropical	Among the ecological services of urban parks in Wuhan, the largest contribution is CO ₂ storage, with a benefit ratio of 69.34% to 73.76%.	[43]
Urban parks	Zhengzhou, China	Large City	Continental monsoon	In the Chinese Green Expo, the average carbon storage density is 40.63 kg·m ⁻² and carbon sequestration density is 2.65 kg·m ⁻² ·yr ⁻¹ .	[51]
Urban parks	Xi'an, China	Large City	Warm temperate semi-humid	Under extremely hot weather, the outdoor CO ₂ reduction potential of urban parks in the Greater Xi'an region reaches 734.3 t CO ₂ /day; indoor CO ₂ reduction reached 814.9 t CO ₂ /day. The total carbon reduction offsets 3.6% of the metropolitan area's fossil fuel carbon emissions. Urban parks in the Yangtze River Economic Belt can offset 5.37% of the daily fossil fuel emissions in the area.	[21]
Urban parks	Beijing, China	Mega City	Warm temperate semi-humid	The average carbon sequestration efficiency of urban parks in Beijing is 8.72g C/m ² per day.	[52]
Urban parks	Yangtze River Economic Belt (YREB), China	Varied	Humid subtropical	Summer heat mitigation allows 26.9 ± 1.5 hectares of urban parks in the YREB area to avoid 23.7 ± 1.6 tons of CO ₂ emissions.1,510 urban parks offset 5.37% of daily fossil fuel emissions in the YREB.	[53]
Urban parks	China's National Demonstration Eco-Industrial Park Sites, China	Varied	Varied	The construction of China's National Demonstration Eco-Industrial Park reduces the carbon emissions of the city by 3.08% mainly by improving the efficiency of energy utilization, and has a strong spatial spillover effect that leads to carbon emission reduction within 450 km of the neighbouring cities.	[56]
Rain garden	Hong Kong, China	Mega City	Humid Subtropical	The average carbon stock in rain gardens in Hong Kong was 7.4 kg m ⁻² .	[66]
Green roofs	Wuxi, China	Large City	Humid subtropical	The annual carbon emission reduction per unit area of the green roof in Wuxi was 9.35 kg m ⁻² .	[44]
Green roofs	Nanjing, China	Large City	Humid subtropical	Different types of green roofs in Nanjing University's Xianlin Campus can reduce CO ₂ emissions by 31,997 - 45,967 kg/day.	[65]
Green roofs	Nanjing, China	Large City	Humid subtropical	Carbon reduction by green roofs of the Kunshan Lou building in Nanjing each year is 4355.6 g CO ₂ ·m ⁻² , of which the direct emission reduction is 46.6 g CO ₂ ·m ⁻² and indirect emission reduction is 4309 g CO ₂ ·m ⁻² .	[64]
Green roofs	Hong Kong, China	Mega City	Humid Subtropical	For a sunny day, the vegetated roof was able to reduce CO ₂ in the surrounding area by almost 2%.	[59].
Green roofs	Chengdu, China	Large City	Humid subtropical	The average carbon sequestration was 6.47 kg C m ⁻² ·yr ⁻¹ . The best carbon sequestration configuration was that of L. vicaryi and was equal to 7.03 kg C m ⁻² ·yr ⁻¹ .	[22]
Green roofs	Japan	Varied	Varied	Annual CO ₂ decrease caused by energy savings varied from 1703 to 1889 kg CO ₂ m ⁻² ·yr ⁻¹ .	[57]
Green roofs	Thessaloniki, Greece	Large City	Mediterranean	Green roofs can help increase carbon storage by 2.5 times.	[67]
Green roofs	Dhaka, Bangladesh	Mega City	Tropical wet and dry	The annual carbon sequestration of green roofs ranged from 20.6 to 125.4 t C/ha, while the CO ₂ equivalent ranged from 84 to 460 t C/ha.	[68]
Green walls	Indonesia	Varied	Tropical forest	Vertical vegetable walls in a student dormitory in a residential area in Indonesia reduced CO ₂ levels by 0.12 ppm.	[58]
Family farm	Shanghai, China	Mega City	Humid Subtropical	The carbon emission reduction potential of family farm facility agriculture and vertical hydroponic technology in Shanghai Chongming Island can reach 9.6e+08 kg CO ₂ eq.	[63]
Urban garden and urban agriculture	Madrid, Spain	Mega City	Varied	Urban agriculture activities contribute to a shift in food consumption towards a low-carbon diet, with an annual reduction of up to 205.1 kg of CO ₂ per person.	[60]

*Mega City refers to an urban agglomeration of over 10 million people, while a Large City typically denotes an urban area with a population between 1 and 5 million, and varied in this research means studies covering multiple cities with different population sizes or administrative levels.

model [71,72,38], which are widely applied to estimate carbon storage and sequestration.

In addition, laboratory-based methods have been used to investigate the carbon emission reduction potential of specific vegetation species [73,74]. For city-scale assessments, remote sensing models such as CASA are commonly employed [75,76], while some studies also apply allometric equations to estimate biomass and associated carbon storage [77, 78]. The following section presents a comparative review of these techniques, highlighting their respective advantages and limitations.

4.1. UGI's carbon quantification methods

Piao *et al.*'s [79] categorised carbon sink estimation methods in terrestrial ecosystems estimation into "bottom-up" and "top-down" approaches. we adopt the same framework to categorize current methods used for UGI. . The "bottom-up" category includes sample plot measurement, assimilation, and laboratory methods, while the "top-down" category encompasses remote sensing methods.

The sample plot measurement involves surveying large-scale plots, converting measurement data, and calculating the carbon sink of the study area using specific formulas [80]. This typically involves the allometric equation method and the process-based ecosystem modelling

method [34]. The allometric equation method uses tree diameter at breast height and tree height as independent variables and biomass as the dependent variable to construct a regression model [81,82]. The modelling evaluation estimates carbon stocks and sources/sinks by simulation of tree growth based on the characteristics of the vegetation itself [83,79], and these methods are widely used in ecosystem services assessments.

The assimilation method measures the instantaneous CO₂ concentration and water flux in and out of plant leaves, calculating carbon sequestration by multiplying the leaf area by the net photosynthetic rate per unit time [84]. The laboratory method involves harvesting vegetation samples, drying them to obtain plant dry weights and densities, and measuring total, inorganic, and organic carbon concentrations to determine plant carbon sequestration and storage [74].

Areas with UGI are typically heterogeneous and dynamic due to accelerated urbanisation and human activities [34]. With advancements in remote sensing technology, scholars have begun using remote sensing models to study the spatial and temporal characteristics and drivers of carbon stocks in urban green spaces [85]. Remote sensing provides spatially explicit and time-sensitive information. Decision makers, researchers, and relevant stakeholders can utilise this data to bolster tailored mitigation and adaptation strategies at specific sites, thereby enhancing resilience to climate change [86].

4.2. Pros and cons

While a wide range of carbon quantification methods has been applied in UGI research, their applicability and performance often vary depending on the specific carbon reduction pathway involved. The basic principles, advantages, and disadvantages of these methods are summarised in Fig. 5.

For carbon sequestration mechanisms, sample plot measurements, allometric equations, and tools like i-Tree Eco are widely used. These “bottom-up” approaches provide high accuracy by using detailed biophysical data, but they are time-consuming and labour-intensive, making them less feasible for large-scale or dynamic urban environments [78,87,88]. Additionally, variations in tree measurements, plot selection, and climatic conditions introduce uncertainties [89], and excessive simplification in growth models may overlook vegetation dynamics [90].

In contrast, thermal regulation and building energy-saving effects,

which represent indirect carbon reduction, are commonly assessed through remote sensing and energy-use simulations, particularly using tools such as CASA and InVEST [79,65]. These “top-down” methods are efficient, scalable, and well-suited for capturing urban-scale patterns [91]. However, their accuracy relies heavily on input data and model parameters. For instance, InVEST requires high-resolution land use data, which can be difficult to obtain in rapidly changing urban areas [92]. CASA, while requiring fewer parameters, is affected by vegetation thickness variability, leading to underestimations of carbon storage [93].

For urban agriculture, which reduces emissions by shortening food supply chains and encouraging low-carbon diets, methods such as Life Cycle Assessment (LCA) or food-miles estimation are more appropriate [94,95]. These methods are useful for estimating systemic impacts but often lack consistent data inputs, limiting their comparability across cases. Other methods, such as assimilation techniques, are effective in assessing the carbon sequestration potential of different species at a small scale but are highly sensitive to meteorological conditions [34]. Similarly, laboratory methods provide precise carbon concentration measurements but are destructive and limited in scale.

In summary, the selection of appropriate carbon quantification methods should not only consider data availability and spatial scale but also be closely aligned with the specific UGI carbon reduction mechanism being assessed. A pathway-based approach improves the accuracy and policy relevance of UGI carbon evaluations.

5. Reasons for variabilities in carbon reduction of UGI

While numerous studies reveal carbon reductions attributable to the presence of UGI, the magnitude of carbon storage and sequestration varies substantially. For instance, research on green roofs in Wuxi indicates an annual carbon emission reduction of 9.35 kg·m⁻² [44], while another study on green roofs in Nanjing reports an annual carbon reduction of 4.36 kg·m⁻² [64]. Similarly, the average carbon sequestration efficiency of urban parks in Beijing is 3.18 kg·m⁻²·year⁻¹ [52], while the average carbon sequestration density at the Chinese Green Expo Park in Zhengzhou is 2.65 kg·m⁻²·year⁻¹ [51]. This variability is linked to several factors, including climate, plant size and age, plant selection, placement, and landscape patterns configuration, each of which will be discussed in turn.

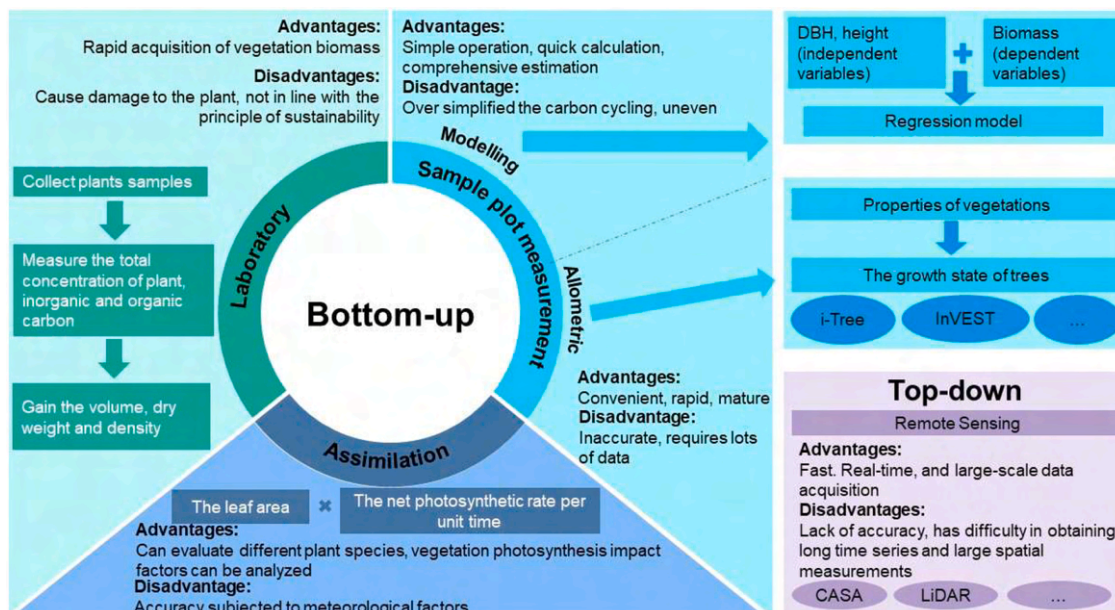


Fig. 5. Principles, advantages, and disadvantages of carbon quantification methods in UGI. Source: Authors.

5.1. Background climate

Among the natural factors influencing UGI's carbon reduction capacity, climatic and biophysical conditions play a central role. The capacity of vegetation carbon sinks is sensitive to meteorological conditions, as climatic factors such as temperature, precipitation, and seasonal variation significantly affect carbon sequestration efficiency. Meteorological variables contribute approximately 48.4% to the observed variability in carbon reduction. Among these factors, temperature exerts the greatest influence on vegetation carbon sequestration [96], as both precipitation and temperature affect biomass changes through soil factors [97], which, in turn, influence the carbon storage capacity of trees.

From the perspective of climatic zones, afforestation in tropical and subtropical regions exhibits strong carbon sequestration capacity, with an average net ecosystem productivity of more than $400 \text{ g C m}^{-2}\text{a}^{-1}$. The temperate zone follows, with an average net ecosystem productivity of $314 \pm 78 \text{ g C m}^{-2}\text{a}^{-1}$, and the lowest productivity is observed in the frigid zone [98].

In cold and dry regions, tree growth is often limited, thereby restricting potential forest carbon storage [99]. For instance, the average carbon sequestration of urban parks in Wuhan (subtropical region) is $7, 161 \text{ g C/m}^2$ [43], which is significantly higher than the average carbon sequestration (8.72 g C/m^2) of urban parks in Beijing [52]. Seasonally, vegetation carbon sequestration is highest in summer and lowest in winter [96]. Green roofs indirectly reduce carbon emissions in the summer and directly reduce carbon emissions in autumn [64]. Similarly, on diurnal time scales, UGI plays a greater role during the day when temperatures are higher [54].

5.2. Plant size and age

The size and age of vegetation are influenced by both biological growth processes and human cultivation strategies. The size of the plant significantly impacts the effectiveness of carbon reduction. Tree height and diameter are directly proportional to carbon sequestration efficiency and carbon storage capacity [100,52]. In the last century, 'big tree transplantation' was popular in China [101], and previous studies have recommended prioritising large trees in park landscape design [102].

Wang et al. [52] demonstrated the importance of medium-sized plants in sustaining carbon sequestration efficiency. Carbon fluxes also vary with the age of vegetation [98]. Typically, older tree species store and sequester more carbon than younger ones [103]. As trees age and their canopy expands, they further increase local vegetation cover [104].

Shang et al. [105] predicted that China's Forest will maintain a high growth rate for the next 15 years. However, by 2100, the forests' age, which directly affects their net primary productivity, will decline by $16.6\% \pm 2.8\%$, implying a weakening of carbon sinks from forests. This decline is attributed to long-term biomass production and nutrient depletion, and older forests tend to have lower nutrient utilisation, resulting in some soil nutrient deficiencies that limit plant growth and slow down forest carbon gain [105].

5.3. Plant selection and placement

Human planning decisions, including species selection, planting density, and spatial layout, are critical determinants of UGI's carbon reduction performance. The size, age, and selection of plants significantly influence their carbon reduction capabilities. Different tree species, for example, exhibit considerable variations in their carbon sequestration potential [106]. Pine trees store a substantially higher proportion of carbon compared to species such as oak (*Quercus* spp.), cypress (*Taxodium* spp.), and maple (*Liquidambar styraciflua*) [103].

In agricultural contexts, such as in Wangarasi city, food crops

generally sequester more carbon than vegetable crops. Within similar plant types, such as peppers and eggplants, carbon sequestration is greater on agricultural land than on non-agricultural land [18]. Shrubs, although possess strong carbon sequestration capabilities, have smaller sizes, which limits their overall carbon sequestration potential [104]. Strategies such as dense planting, group planting, and clustering can enhance the leaf area index and canopy width, significantly boosting total carbon sequestration [107].

Regarding vegetation placement, tree-based intercropping in urban agriculture generally results in higher carbon sequestration, both above and below ground, compared to monoculture cropping systems [108] owing to trees' enhanced capacity to capture CO_2 [109,110]. For other UGI systems, such as urban parks or open green spaces, strategic clustered urban development alongside the preservation of old-growth forests can sustain up to 91% carbon storage and 82% carbon sequestration [103]. This clustered design not only supports carbon storage and sequestration goals but also helps preserve biodiversity and reduce carbon emissions by minimising the need for extensive road networks and vehicle travel.

Vegetation density also influences carbon sinks, with higher densities generally enabling greater carbon sequestration [104]. Yet, this does not advocate for indiscriminately dense plantings, particularly in urban settings. High tree densities can reduce wind speeds, potentially trapping pollutants and leading to elevated concentrations of urban pollutants [111]. Moreover, dense vegetation can increase pollen allergies [112]. Therefore, careful consideration of plant selection and placement is crucial to optimise carbon storage and manage carbon emissions effectively.

5.4. Landscape patterns configuration

Among the key anthropogenic factors, landscape patterns play a crucial role in shaping the carbon reduction potential of UGI. Numerous studies have demonstrated strong associations between urban spatial configurations, carbon emissions, and sequestration [13,113,114]. In particular, subtle variations in landscape structures surrounding urban forests (patch size, shape, fragment, complexity, and connectivity) can significantly influence their carbon sink capacities [115].

The size of landscape size is consistently correlated with carbon sequestration [116]. Li et al. [117] examined the linear and nonlinear relationships between various GI landscape metrics and urban carbon budgets across 31 Chinese cities from 2001 to 2021. Their findings show that increases in green space area and compact, aggregated GI structures generally enhance both carbon sequestration and emissions reduction. Higher levels of adjacency and connectivity are positively correlated with enhanced carbon sequestration capacity [118].

Recent studies suggest that the fragment of landscape patches may significantly affect carbon absorption capacity, with increasing fragmentation associated with greater carbon loss [119]. This is due to the lack of ecological synergy among fragmented carbon sink patches, which compromises their capacity to function effectively as a unified carbon sequestration system [120]. For instance, in Guangzhou, habitat fragmentation and the associated edge effects were found to significantly impair the carbon storage capacity of forests in human-modified landscapes [121]. Similarly, Guo et al. [122] noted that higher forest patch density (an indicator of increased fragmentation) correlates negatively with carbon sink potential. When fragmentation exceeds a certain threshold, green patches may lose their carbon sink functionality altogether [123].

The shape and complexity of landscapes have also been identified as potential driver of carbon emissions [124]. According to Yuan et al. [118], increasing the shape complexity of green-blue patches can significantly enhance carbon sequestration. Higher aggregation, adjacency, and connectivity levels, coupled with reduced fragmentation, are positively correlated with improved carbon sink capacity. While complex UGI landscape shapes can support greater carbon uptake, they may

also inadvertently contribute to higher emissions [117]. This aligns with observations from earlier studies of Shu and Xiong [125] and Tang et al. [126], which found that declining landscape complexity and connectivity were associated with higher carbon emissions. However, research in Nanjing by Yuan et al. [118] showed that expanding the area and increasing the shape complexity of green-blue patches can significantly enhance carbon sequestration. Therefore, maintaining the connectivity and integrity of green spaces and minimising fragmentation and irregular edges are essential for optimising carbon sequestration [124].

6. Multi-scale policy recommendations and future pathways for mainstreaming UGI towards carbon neutrality in China

China acceded to the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [127], it has historically adopted a passive stance on climate change mitigation. It was not until the launch of the Bali Roadmap in 2008 [128] that China began to respond more proactively to climate change. Subsequently, China aligned with global climate efforts, pledging in 2020 to achieve peak carbon emissions by 2030 and carbon neutrality by 2060 [129] (Fig. 6). The Chinese Government, academia, and the public are increasingly recognising the need to balance economic growth with environmental protection, resource conservation, and CO₂ emissions reduction. In response, the government has enacted a series of policies and legislation to address these concerns [130].

6.1. Multi-scale policy recommendations for UGI implementation

China's approach to climate governance has evolved significantly over the past three decades, providing the institutional foundation for the development and mainstreaming of UGI strategies. According to Wu [131], China's climate policy has evolved through three distinct stages (Fig. 7). From 1988 to 2006, economic development significantly overshadowed climate concerns, with emissions reductions primarily

considered within the realm of foreign affairs. A pivotal shift occurred in 2007 [132], which integrated climate commitments into legal obligations within China's '11th Five-Year Plan' (2006-2010) and '12th Five-Year Plan' (2011-2015). This integration spurred a surge in climate change adaptation practices and research [133]. The 'Five-year Plan' (FYP), a critical national policy instrument, outlines clear strategies for national management and implementation [134]. In the same year, the State Council established the "National Leading Group for Climate Change Response" to ensure inter-ministerial coordination of climate policy [135] and introduced 'the National Climate Change Programme', China's first comprehensive climate policy aimed at both national and international contexts [136].

The second phase of policy development saw inadequate monitoring of adaptation policies and a weak assessment of their effectiveness [137]. Following the adoption of the Paris Agreement [1], China entered its third phase (2016-present), where climate goals were integrated into the 13th FYP and 14th FYP, leading to significant advancements in carbon reduction policies [138]. This ongoing phase reflects China's strengthened commitment to addressing global climate challenges through enhanced policy frameworks and strategic national planning.

At the national scale, China's climate policy system follows the "1+N" model, where '1' represents the guiding ideology and top-level design to reach peak carbon by 2030 and carbon neutrality by 2060, and 'N' refers to action plans for key sectors [139]. To implement these goals, the central government has launched a series of large-scale ecological programs that directly contribute to carbon sequestration and green infrastructure development. For instance, during the COP21 in Paris in 2015, China announced a voluntary reduction target of 4.5 billion m³ in forest stock by 2030, equivalent to 31.6% of the carbon stock compared to 2005 [140]. As part of its policy to mitigate climate warming, China has invested heavily in national ecological restoration projects, such as the 'Natural Forest Protection Project' [141], the 'Grain for green project' [142], and the 'Beijing-Tianjin sandstorm source control project' [143]. These projects demonstrate how top-down

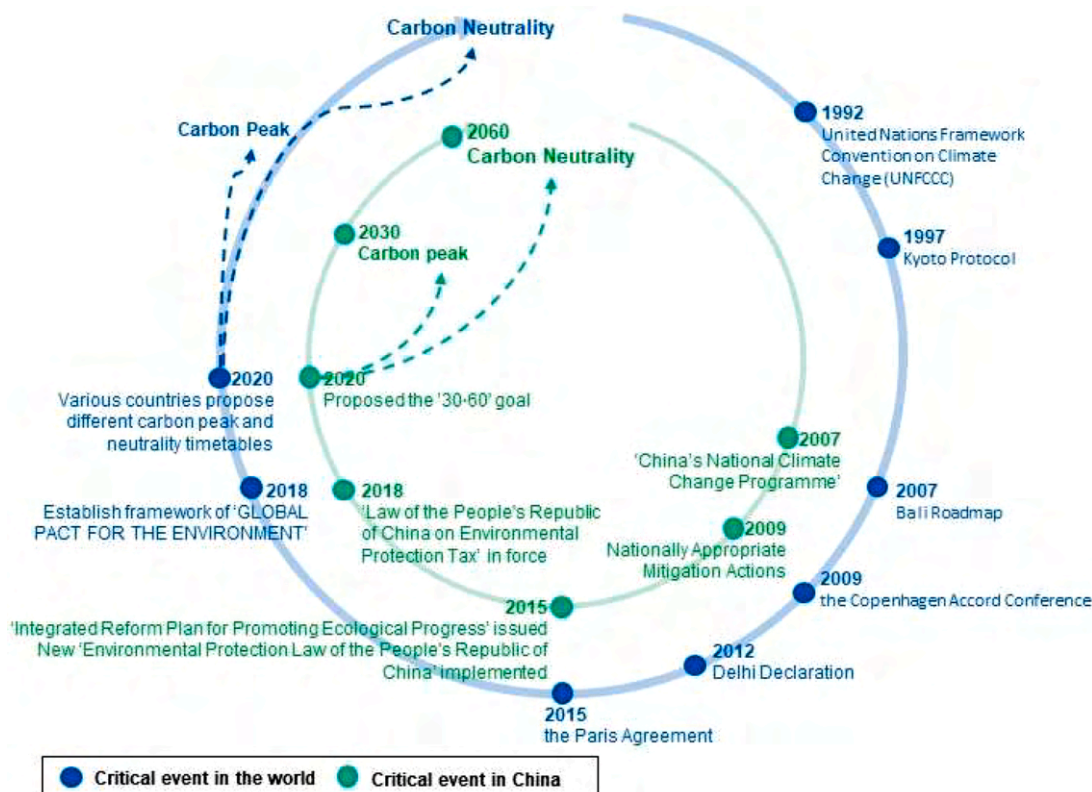


Fig. 6. Critical timeline of climatic events, policies, and actions in the world and China. Source: Authors.

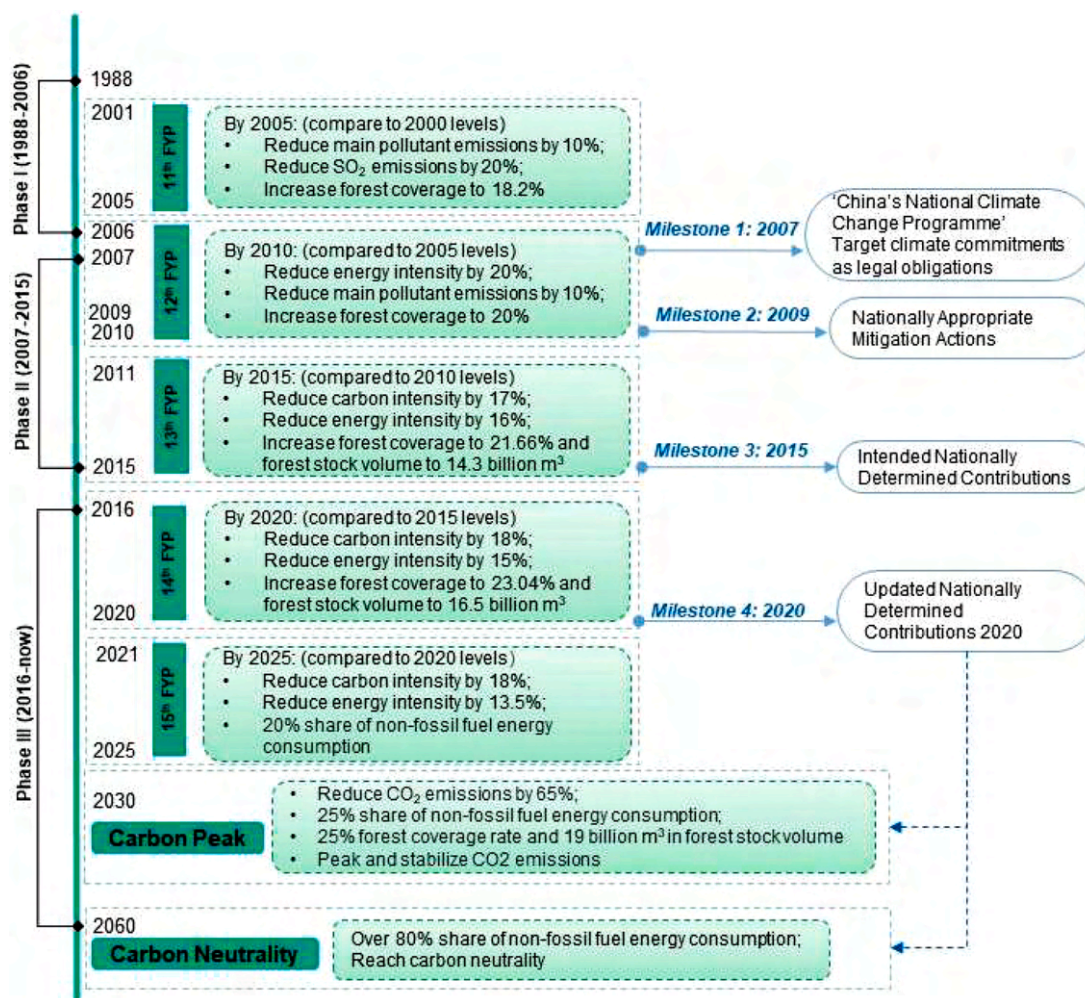


Fig. 7. Timeline and milestones for climatic policies and actions in China. FYP refers to the Five-Year Plan. Source: Authors.

ecological investments can support UGI expansion, especially in peri-urban and rural–urban transition zones.

At the regional level, UGI is being integrated into large-scale spatial planning and ecological management frameworks. Policies promoting regional ecological corridors and green belts have been implemented across major metropolitan regions, including the Beijing–Tianjin–Hebei (Jing-Jin-Ji) area, the Yangtze River Economic Belt, and the Guangdong–Hong Kong–Macao Greater Bay Area. These policies emphasise coordinated action across jurisdictions, aligning regional planning with watershed protection, pollution control, and biodiversity conservation [136]. Additionally, the Ecological Redline Policy serves as a regulatory tool to designate and protect critical ecological zones, often overlapping with key UGI spaces [144]. This regional policy ensures that high-carbon-risk land uses do not encroach upon green infrastructure or compromise its long-term carbon sequestration capacity.

Moreover, China has promoted various programmes at the local scale, with numerous cities designated as pilot zones for UGI-related climate strategies. Notable initiatives include the ‘National Ecological Garden City’ in 2004 [145], the ‘Low-Carbon City’ in 2010 [146], the ‘Sponge City Program’ (SCP) in 2013 [66], and the ‘Climate Adaptation City’ in 2017 [147]. These programmes encourage municipalities to incorporate UGI into urban development plans, emphasizing multi-functionality such as carbon sequestration, flood control, and urban cooling. A particularly instructive example is Hong Kong, which operates under the ‘One Country, Two Systems’ framework [148]. Despite having only 276.6 km² of developable land [149], Hong Kong maintains over 70% green coverage [150]. Its success is attributed to

both top-down planning and grassroots action. Even before climate adaptation became a major policy focus, Hong Kong invested heavily in green urban infrastructure like sewage treatment and hillside vegetation, setting a model for high-density urban UGI integration [151].

6.2. Future pathways for mainstreaming UGI

To achieve its 2060 net-zero emissions target, China must navigate a complex landscape of both opportunities and challenges [129]. While government leadership is essential for advancing climate adaptation, meaningful carbon reductions ultimately require concerted public engagement and multi-stakeholder action [152].

At the national level, the mainstreaming of UGI requires stronger institutional integration across climate policy, land-use regulation, and environmental performance evaluation. A critical step is the acceleration of improvements to China’s carbon accounting system [153], incorporating it into green evaluation systems [154], particularly within the ‘1+N’ climate governance architecture.

To achieve this integration, dual-carbon-oriented policies must be strategically designed with clear definitions of responsibilities for key stakeholders, including government agencies, enterprises, academia, and the public. Such clarity will ensure precise, coordinated, and effective implementation [155]. Moreover, these policies should adopt a forward-looking approach, integrating carbon goals with broader national development strategies and long-term structural reforms in energy, industry, and transportation. Incentive mechanisms must also be expanded, with dedicated green financing tools (e.g., ecological

compensation, carbon trading credits, and green bonds) being used to reward cities and provinces demonstrating effective UGI deployment [156].

At the regional scale, future strategies should emphasise cross-boundary ecological coordination, as climate and carbon challenges often exceed administrative limits. UGI can act as a spatial and ecological connector across urban agglomerations and support joint carbon reduction efforts. In shrinking or transitioning cities, customised UGI strategies are essential to address both economic and environmental pressures [157]. Therefore, policies should be tailored to the specific roles and development needs of each urban cluster [158], with adaptive UGI masterplans that include flexible zoning, shared carbon inventories, and collaborative planning platforms. To strengthen regional synergy, platforms for inter-city and public-private knowledge exchange should be established to support programs like the Low-Carbon pilot city [159]. Multi-scalar co-benefit evaluation systems are also needed to assess UGI's contributions beyond carbon, including biodiversity, cooling, and health.

At the municipal and neighborhood level, the emphasis must shift toward participatory governance and co-production of UGI. UGI strategies have been integrated into urban planning and policy frameworks such as comprehensive plans, zoning ordinances, and building codes [160]. While these initiatives encourage the use of UGI to varying degrees, the potential for UGI to reduce carbon emissions has been overlooked or given little consideration [161]. In Europe, UGI has been successfully promoted as an urban heat mitigation tool in response to increasing heatwaves, the awareness of the urban heat phenomenon, and the resulting demand for air conditioning [162]. These international practices highlight the importance of public engagement and targeted policy support. Hence, local authorities should also strengthen public education and outreach, using media storytelling to highlight the climate and social benefits of UGI [163].

As Liu et al. [129] call for, there is a need to broadly incentivise bottom-up efforts, such as setting local mitigation targets with emission caps, promoting a just transition to carbon neutrality, and mobilising communities and society. Grassroots movements play a crucial role in the transition to a low-carbon society [164]. Cities should pilot community-led UGI projects, such as pocket parks, green roofs, and street trees. A notable example of this approach is seen in Hong Kong experience, where UGI has been effectively embedded into a high-density, limited-land environment through early infrastructure investment and zoning, providing a valuable model [148,151]. Zhang et al. [165] contended that the lack of promotion and incentives has become a primary barrier to UGI construction. Accordingly, there is a need to provide incentives, regulations, and guidelines to encourage the adoption of UGI in private and public development, such as demonstrating the benefits of UGI and reducing maintenance costs [166,160]. Moreover, planners and designers should extend their roles beyond technical experts to become facilitators of inclusive urban transformation, engaging citizens in decision-making and co-design [167, 168]. This approach can maximise the full potential of UGI in the urban environment [169,170].

7. Conclusion

As the world's largest carbon emitter, China is positioned to play a pivotal role in global climate governance, particular in its commitment to achieving carbon neutrality by the 2060s. UGI represents a strategic asset in this endeavour, contributing not only to long-term environmental sustainability but also to climate adaptation at multiple scales.

Based on this review, UGI contributes to carbon reduction through three primary mechanisms: 1) carbon storage and sequestration, 2) reduction of energy demand for cooling and heating by mitigating anthropogenic heat, and 3) overall reduction in carbon emissions and urban carbon footprints. These mechanisms are essential components of an integrated strategy for achieving carbon neutrality.

However, the effectiveness of UGI in delivering carbon reduction benefits is influenced by several factors, including meteorological conditions, the size, age, and type of vegetation, the spatial arrangement of the vegetation, and landscape patterns. Therefore, urban planners and policymakers are encouraged to optimise spatial planning and UGI layout strategies to maximise climate benefits. For example, increasing the distribution of medium-sized trees across UGI facilities and applying targeted carbon reduction strategies in high-emission or high-exposure areas can enhance the impact of UGI interventions.

Despite its considerable advantages, China's predominantly "top-down" governance model has thus far underutilised the potential of UGI in advancing carbon neutrality initiatives. To rectify this, it is imperative to mainstream UGI as a key instrument in national and local climate strategies. At the national level, governance frameworks should prioritise the integration of UGI into carbon accounting systems and national green evaluation mechanisms, supported by appropriate financing instruments and policy incentives. At the municipal or city-regional scale, UGI should be embedded into adaptive spatial planning, inter-city ecological coordination, and sectoral climate action plans. In parallel, encouraging "bottom-up" engagement is essential. This includes incentivising the integration of UGI in both private and public developments, particularly in high-density urban residential areas, and raising public awareness of UGI benefits through media outreach. Strengthening collaborations with relevant organisations and stakeholders is also crucial to ensure policy coordination and coherence, thereby advancing the broader development agenda and accelerating progress toward carbon neutrality.

Future research should prioritise the development of more refined carbon quantification methods tailored to specific UGI mechanisms and spatial scales. In particular, the integration of advanced technologies, such as machine learning and high-resolution remote sensing, offers promising avenues for enhancing the spatial and temporal accuracy of carbon assessments. Further investigation is also needed into how specific UGI typologies and configurations, including the distribution of vegetation types across different urban densities, can be optimised to maximise carbon mitigation outcomes.

Another key research priority is the evaluation of long-term synergies and trade-offs between carbon reduction and other co-benefits (e.g., public health improvements and biodiversity conservation) across diverse climatic and socio-economic settings. Additionally, greater attention should be paid to institutional factors, including governance frameworks, inter-agency coordination, and financing mechanisms, which critically shape the effectiveness and equity of UGI implementation. Addressing these targeted research gaps will generate actionable evidence to support the strategic integration of UGI into China's carbon neutrality agenda.

CRedit authorship contribution statement

Sitong Liu: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Meili Feng:** Writing – review & editing, Supervision. **Linjun Xie:** Writing – review & editing, Supervision. **Faith Ka Shun Chan:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial and other conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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