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Review

A Review of the interrelations of terrestrial carbon sequestration and urban forests

Running title: Terrestrial carbon sequestration and urban forests

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Abstract: Rapid urbanization poses major challenges to the mankind with huge impact on the society and the economy. This paper aims to review relevant literature, mainly recent studies, focused on significant aspects of the interrelations of urban forests and terrestrial carbon sequestration, discussing their implications with reference to urban forests and their roles in climate mitigation, given that the real challenge lies in understanding the integration of carbon sequestration having huge pollution mitigating potentials with other mitigation options. Findings suggest that despite indications of studies that urban forests play significant mitigation roles; they have not been accorded adequate importance vis-à-vis management of ecological disturbances. Findings also suggest that urban forests significantly contribute to terrestrial carbon sequestration and these contributions are in addition to their multiple social-economic-cultural-aesthetic benefits. This paper underscoring the significant contributions of urban forests in maintaining ecological equilibrium, and managing balance between emissions and sequestration to ensure sustainability, offers usefulness to the future researchers, academics, urban-planners and policymakers.

Keywords: carbon sequestration; climate change; urbanization; urban forests

Abbreviations: C: Carbon; CCS: carbon capture and sequestration; CO_2: Carbon Dioxide; CO_2e: CO_2 equivalents; DBH: diameter at breast height; GBH: girth at breast height; GHGs: Greenhouse Gases; GIS: Geographic Information Systems; ppm: parts per million; UNFCCC: United Nations Framework Convention on Climate Change

1. Introduction

Marzluff [1] argues that urban is defined in environmental sciences in terms of dominant land cover whereas it is associated with population density in social sciences. Climate change and Global warming resulting from emissions of CO_2 and other GHGs are causing the environment and atmosphere to degrade significantly [2]. Fossil fuel burning-Land use changes-Industrial effluents are some of the main human induced activities responsible for increasing CO_2 emissions in the atmosphere. Slow response of climate towards these changes in CO_2 levels amply indicates that global mean temperature would keep rising even though carbon emissions are stopped today, and even then other climate impacts would keep increasing for next few decades or centuries. The rate at which carbon is deposited into living organisms is not the same as the rate it is returned to our planet [3].

CO_2 is dominant amongst GHGs [4] and trees act as sink which fixes carbon through photosynthesis and stores excess carbon as biomass [5]. In the present scenario of continuously increasing concentration of CO_2, growing interest is being witnessed in studying the potential of increasing carbon storage in terrestrial vegetations through forest conservation, and through afforestation–reforestation-land use change–land cover management. IPCC's special report on land use changes and forestry suggests that there is huge untapped potential to sequester an additional 87 Pg C by 2050 in global forests alone [6]. However, carbon sequestration, an activity to store carbon or its other forms for global warming mitigation which was one of the important clauses of erstwhile Kyoto Protocol, is considered significant in urban areas also because of the greater net savings in carbon emissions achieved by urban vegetations. To make more sustainable cities in future, there is a need to minimize and manage the ecological disturbances keeping in view the significance of urban trees in storing and sequestering carbon in addition to their aesthetic contribution, scenic beauty and other incomparable benefits [7].

The structure of this paper is as follows. The ensuing section presents a brief account of the materials & method. Subsequent sections prepare the readers for enhanced understanding of the background elaborating the urbanization-environment linkages, carbon emissions and climate change, global market value of carbon, significance of terrestrial sequestration, assessment of carbon sequestration, and costs-services-issues related to urban forests, providing the much needed underpinnings to the efforts of meeting the main objective of the study in the subsequent sections, based on the critical review of the previous relevant studies.

2. Materials and methods

Taking into consideration the context of urbanization, its planning and management of ecosystem services amidst the continuously increasing impact of climate change and global warming, this paper sets its objective as to make an attempt to present a review of the extant literature on different significant aspects of the interrelations of urban forests and terrestrial carbon sequestration discussing their implications with reference to urban forests and role in climate mitigation given that the real challenge lies in understanding the integration of terrestrial carbon sequestration with other climate change mitigation options. This extensive literature review is focused mainly on the studies conducted in recent two decades collecting materials by means of online searches of reliable electronic databases comprising mainly Google Scholar, Web of Science, Science Direct, Scopus amongst others, using keywords such as urban, forest, carbon, sequestration and combinations thereof. However, subjective interpretations based on the contents in their abstracts played significant role in preparing the final list of studies taken for this review.

3. Urbanization-environment linkages

United Nations [8] reports the huge expansion of cities around the world not only in number but also in size, demonstrating fast increasing urbanization in the last century estimating that global population has reached 4 billion in 2015 as against 746 million people in 1950 showing a five-times growth, expecting at the same time the continuance of the same in following decades more particularly in the low- and middle-income countries posing huge challenges for them in managing urbanization. In today’s world, the demographic situations in cities across the world are putting their environmental sustainability and the well-being of their inhabitants at stake. Nowak [9], emphasizing the huge effect of urban forests on the routine life of human populations, informs that in excess of 80 per cent of the population in the USA lives in urban areas. The expansion of cities and its intensification-without due considerations to the land use capacity and local needs for food, woody building materials and wood energy-have contributed immensely to the drastic depletion of trees and forests covers in and around urban areas [10,11].

Cities suffer from floods, dust encroachments, water shortage, soil erosion and landslides, costing them significantly in terms of lost infrastructure and human deaths. Nonetheless, their natural ecosystem affected heavily by the increasing impacts of urbanization plays a significant role in preserving and enhancing biodiversity. Fast economic development can be detrimental to environment due to land use changes, higher consumption of resources, and pollutions [12]. Significant volumes of literature stress on the contribution of urban forests in reducing pollution levels, and offsetting GHGs emissions in cities [13–18]. Suitable management and maintenance of urban forests and green spaces, therefore, are immensely critical in order to maximize the health benefits, given their ability to provide multiple benefits [19].

Humans have extensively altered the global environment, changing global biogeochemical cycles, transforming land and enhancing the mobility of biota. It has continuously been rising in the atmosphere since the era of Industrial Revolution which is believed to be responsible for causing disturbances in energy balance of the planet, and for accumulation of energy leading to ice melting-sea level rise-ocean/atmosphere circulation changes-extreme weather changes-floods etc. [20], significantly affecting food production and causing other irreversible consequences. Cities which represent the urban areas offer themselves to be the hubs of socio-economic development. However, rapid urbanization, on a planet having scarce resources for accommodating growing needs of food and other basic services, is an obstacle in ensuring equitability and sustainable urban development (United Nations, 2016). As urban areas are characterized by complex adaptive systems, the concept of ecosystem services represents an important tool for the management of urban socio-environmental quality which can be applied to climate change adaptation and mitigation strategies which also relates to the main issues including poverty-human settlements–environment–health–land-good governance etc. [21].

Cities are unlikely to develop in a sustainable and healthy manner without the systematic integration of tree-based systems and forests into land use in and around cities, and adequate understanding of such systems' relationship with demographic and environmental issues [15]. Unfortunately, they have not been given significant attention at policy and decision-making forums at the international–national–regional–municipal-local levels. Appreciations of urban areas as complex adaptive systems allow urban planners and decision-makers to effectively manage individual ecosystems in specific urban areas. The process of urbanization brings multiple economic and social benefits to urban ecosystems but its direct and indirect negative impacts on urban ecosystem are readily apparent. The urban population in the Asian region, having 17 of the most densely populated and 12 of the most populated 25 cities in the world, is increasing at a rapid rate where rapid population growth is often not matched by increased services and facilities, leading to deterioration of urban environments [22], despite the evidences showing that 2.4 million trees planted in the city centre in Beijing removed 1261.4 ton of pollutants from air [16].

Borelli et al. [23] showcase the acknowledgements of the international agencies including the United Nations as regards rapid and unplanned growth in urban areas which has driven inequality and poverty, more particularly in the newly urbanizing countries. In order to enhance understanding the linkage of urbanization and environment, it would be helpful to have knowledge of the related issues in different time eras focusing also on the significance of urban forests. More than four decades ago in 1976, the first Habitat Conference was held in Vancouver (Canada) which successfully attempted to draw global attention, emphasized on an urgent need for initiation of serious discussions on the issues related to unsustainable urbanization, and also paved the way for the birth of the Intergovernmental UN Commission on Human Settlements, and the UN Centre for Human Settlements, which finally led to the emergence of the UN Human Settlements Programme (commonly referred to as UN-Habitat). Two decades later in 1996, took place the second Habitat Conference at Istanbul (Turkey) bringing about the endorsement of a significant policy document i.e. the Habitat Agenda which intended to ensure urban sustainability by setting a plan of action. Urban sustainable development has been accorded greater priority in the Agenda 2030 for Sustainable Development of the UN and the Paris Climate Agreement of the UNFCCC (UN Framework Convention on Climate Change), both of which came in existence in the year 2015. This was followed by the third Habitat Conference held in Quito (Ecuador), in 2016, ending with the endorsements for the New Urban Agenda (NUA), providing a global roadmap for future decades for ensuring sustainable urbanization, laying emphasis on the adoption of people-centric thriving strategies for sustainable and inclusive urban economies with environmental sustainability in developing as well as developed countries. Borelli et al. [23] underscore that cities can harness the potential of urban forests in achieving a greener and healthier planet ensuring the well-being of the entire human population. They highlight the commendable joint efforts of some of the active networks at national, regional and global levels underscoring the significant role of urban forests and trees in ensuring sustainable urban development across the globe. The key role of urban forestry has received huge recognition as the event such as the First World

Forum on Urban Forests (in Mantova, Italy in 2018) has started to take place in recent times, demonstrating increasing interests in urban forests suggesting to optimize their potentials by bringing together people, representatives of international organizations, governments, research and academic institutions, urban planners and foresters, professionals, NGOs etc. in order to ensure and achieve a greener and healthier planet in future [23].

Konijnendijk and Randrup [24] posit that despite the earliest interest in urban forests contributing to more attractive cities shown as early as the ancient age of Roman/ Greek Civilizations, interest in their more recreational and aesthetic benefits emerged in the Renaissance and mercantilist era when a newly emerged wealthy class displayed interest in them for leisure, economic and prestige purposes. During industrial revolution, the city authorities supported by the industrialists showed enhanced interest in urban forestry at a time when huge number of workers reached and started to live in these cities. Nonetheless, it was only in modern times that planning and managing urban forests became the established parts of municipal activity. They further add that the growing urbanization brought with it a growing demand from urban citizens for urban forests, in previous century, leading to the emergence of the concept of urban forestry initially in North America, leading to the introduction of the term 'urban forestry' in 1965 which, despite initial resistance, gradually received greater scientific, political, and professional support not only in North America but also across the globe during the 1980s. It is notable that only in recent few decades, urban forestry has found place in more established global research activities separated from forestry which has been highly supportive in advancing the concept of urban forestry in different disciplines. Urban forestry, despite proximity to forestry, tends to be multidisciplinary more than forestry and has witnessed development of more integrative research.

4. Carbon Emissions and climate change

Carbon is omnipresent with its existence in atmosphere–oceans–soil–rocks-fossil fuels-living organisms which keeps getting cycled throughout the earth system continuously [25–27]. CO_2 is referred to as the primary GHG mainly responsible for climate change which has surpassed a very high reading of 400 ppm in the atmosphere [28]. Accurate assessment of CO_2 emissions caused by various anthropogenic activities, including but not limited to changes in land use, is the major challenging issues for understanding global carbon cycle and for making important policies [29]. Fossil-fuel combustion and deforestation have increased the concentration of atmospheric CO_2 by 30 per cent in the previous three centuries with a substantial increase occurred in past forty years in excess of 50 per cent, along with other GHGs that significantly contribute to global warming [30].

Threats of pollution, global warming and their effects are responsible for causing rise in global temperature leading to multitude of other associated problems [31]. It warns against any delay in realizing that absorption and releasing of CO_2 help us in understanding the climate and predicting global warming. Given that carbon is not stable in nature, it is important to learn where it is being stored and released [32] keeping in view also that big trees deplete more air pollution and capture/store carbon than small trees annually [33]. Metrics to track changes in a meaningful way for humanity are the need of the hour along with the suitable ways of keeping the population at large appropriately communicated so that they can be persuaded to understand the importance of mitigation and adaptation measures for successful implementation of climate change addressing policies. Indicators, therefore, need to gauge risks as well as changes in addition to the series of above events [34]. Nonetheless, appropriate indicators must be useful-actionable-reliable-robust-verifiable-worth forecasting, and should be embedded as part of an understandable story for people while communicating information about climate change for facilitating them in relating to them instead of considering them as mere numbers [34].

GHGs are released mainly using fossil fuels such as coal and petroleum. industrial processes and livestock farming are also relevant emission sources. Rising levels of GHGs warm the atmosphere leading to global warming with diverse negative impacts including but not limited to rising sea levels -increased risks of flooding–drought-other extreme weather events [35]. International communities have shown consensus to limit the temperature increase to 1.5 ℃ while making utmost efforts to keep it below 2 ℃, at the COP 21 under UNFCCC held in 2015 in Paris which can only be achieved by rapidly reducing global GHG emissions. CO_2, therefore, is found to be one of the main externalities of anthropogenic activities whose emissions, accelerated by deforestation, have resulted in to a substantial increase (25%) of atmospheric CO_2 concentration over the last one and a half century and this trend is still not decelerating [36] causing huge climate change. Measurement of GHG emissions, over the growing cycle, needs to be done in terms of CO_2e while assigning due considerations to the potentials of N_2O and CH_4 in global warming [28]. Studies thus suggest that the most drastic impact of the CO_2 emissions is the accelerated GHG effects and projected global warming. They have been showcased through diverse sets of national and international carbon research agendas consistent with these objectives developed in recent past.

5. Carbon: value in global market

Trading of GHG, particularly CO_2, emissions is being considered an economically sensitive strategy not only at the national but at international level also with the intent to decrease their atmospheric concentrations. The most significant amongst the CO_2 emission trading approaches are carbon credits, carbon trading and carbon markets. While a carbon credit denotes a tradable permit/certificate encompassing the right of one ton of CO_2 or CO_2equivalent emissions, carbon trading denotes permission for the industries unable to reduce CO_2 emissions practicably, for purchasing credits from the industries having reduced their emissions already in excess of their commitments [37]. Emergence of carbon credit gave rise to the very idea of striking consensus among different nations by agreeing to trade in carbon credits which subsequently was signed and sealed as agreements almost a decade ago.

World Bank estimates that the global value of carbon pricing schemes is worth USD 82 billion. As regards carbon value, carbon trading, also referred to as emission-trading, is a market-based tool with the intent to limit GHG emissions. Carbon markets trade them either using cap-and-trade schemes or with credits they pay for or offset GHG reductions. The resulting funds have latent potentials of extending support in avoiding, in emerging or developing markets with lower emission reduction costs, greater amount of carbon [38]. Given that the emission reduction costs are greater than the cost of credits; this carbon trading market has been significantly considered as an economic approach. As an appropriate alternative, the industrial investments can be in the projects related to reforestation for the purpose of removing atmospheric CO_2 biologically using the mechanisms of photosynthesis and carbon fixation from the atmosphere [39]. This is, however, noteworthy that despite this approach being typically considered as reduction and not credit, the process is monitored for a period while measuring units in ton of CO_2, wherein carbon equivalents can be earned as well as traded on the reduction in other GHGs.

6. Significance of terrestrial carbon sequestration

Carbon sequestration denotes the phenomenon of the storage of CO_2 from the atmosphere to mitigate global warming [40], and is referred to as the sequence of processes whereby carbon emitted from large-scale CO_2 emission sources is separated, recovered, and stored under the ground or at sea [41]. Further incineration helps the biomass re-emit carbon back into atmosphere [42]. Human activities also considered as anthropogenic causes of climate change mainly include land use change, development, deforestation, and emissions of GHGs that amplify the greenhouse effect. An issue of global concern today is rapidly increasing levels of CO_2 in the atmosphere and their potentials to change the natural climate across the globe [43]. Although there are many methods of carbon sequestration that are currently being researched, the most important amongst them are terrestrial carbon sequestration and storage in biomass [44] given that forested biomass regions globally sequester 466 gt. carbon each year [6]. With the implementation of proper management and forestation policies, the amount of CO_2 being sequestered annually by biomass has a potential to increase substantially [45]. The role of terrestrial ecosystems in the climate change mitigation is an important component as per the Fourth Assessment Report of IPCC [46].

Soil carbon is comprised of a complex array of compounds. Stable forms are organic molecules that are chemically tied to the mineral soil. Stabilized soil carbon has a residence time of many decades [47]. Carbon accumulated on the surface, e.g. forest floor materials, has a much shorter residence time and is more vulnerable following disturbance. The first and most significant option to enhance carbon sequestration potential of forests lies in the establishment of new forests either through afforestation or reforestation while a second option is to nurture the slow formation of a stabilized soil carbon pool. Although smaller than agricultural soils, the carbon sequestration potential in forest soils is large. About two-third of terrestrial carbon is sequestered in the standing forest, forest under storey plant, leaf and forest debris and in forest soils [48].

Findings of the study conducted on Indian natural forests by Khurana [49] suggest that the rate of carbon sequestration could be increased by means of sustainable forest management regimes to higher level. Estimated rate of carbon flux in selected Indian planted forests reveals that planted forests of short-rotation tree species with regular leaf shedding patterns have more capacity for Carbon sequestering in litter which decomposes more rapidly than those with annual or bimodal leaf shedding patterns [50]. Mixed planted forest of exotic and native species could be more efficient in sequestering carbon than the monocultures. Carbon sequestration in Indian forests at national level and site-specific situations offers some possible opportunities for sustainable carbon forestry [49]. The assessment of forest biomass can eventually provide information on the structure and functional attributes of forests [51].

Expanding developmental activities such as industries, constructions, transports, vehicles and power plants in cities cause huge pollutions [52]. To combat the harmful effects of the concentration of GHGs, especially CO_2, needs to be managed in order to keep it at the lowest possible limit. Studies have also emphasized the potential of carbon capture and sequestration (CCS) in order to mitigate global warming [53]. Naturally, trees fix carbon in the process of photosynthesis and store carbon as biomass and therefore play major role with respect to being a sink for CO_2 [54] in urban areas too. Trees act as an important contributor in capturing atmospheric CO_2, as they grow by sequestering CO_2 in their body including trunk, branches and roots, resulting in an increase in their biomass which hints at an increase in carbon sequestered by them [55]. For the purpose of measuring GHGs pools and fluxes from terrestrial biosphere related to changes in land-use and land-cover, biomass is being increasingly found useful in recent times [56]. Lal [57] posits that likewise soil-vegetation systems also play an important role in the global carbon cycle. Soil contains about three times more organic carbon than vegetation and about twice as much carbon than is present in the atmosphere [25,58]. Terrestrial vegetations and soil currently absorb 40% of global CO_2 emissions from human activities [59].

Health and the functioning of ecosystems are amply indicated by carbon sequestration [60]. In one recent review [61], it was found that 33.7 per cent of total carbon emissions (approx. 3.61 Pg C per year) were removed by terrestrial carbon sinks. Carbon sequestration through plantations is one of the important mitigation measures against rising levels of atmospheric CO_2 and GHGs [62,63]. A study [64] emphasized the huge potential of carbon sequestration in reducing atmospheric carbon. With the growing interest in lowering the emissions rate of GHG from different types of land-use, there is a need of increased focus on forestry and agro forestry systems for carbon sinks which will be necessary to achieve a significant long term reduction in atmospheric GHG levels (carbon and methane), particularly from tropical areas [65,66].

Anthropogenic factors, that influence tree cover, include tree planting/mortality/removal from either direct or indirect human actions such as development and pollution [67]. In urban environment, trees offer double benefits by removing carbon from atmosphere and storing in biomass, and provide stability or remediate natural system with increased nutrient or mineral recycling by biochemical process, and in turn maintain stable climatic conditions. Carbon sequestration potential of trees varies with the type of plant species. As per an estimation [36], the average sequestration rate of CO_2 per tree species is about 11 Kg having a crown area of 50 square meters. Carbon sequestration potential in trees depends on its growth pattern and wood density. It is notable that a fast-growing tree with age less than ten years store more carbon than slow growing species especially in initial stages of life. Later the slow growing species store more carbon in tissues than fast growing species because of its high biomass and wood density in long term [44,68]. As carbon sequestration occurs, individual tree acts as carbon sinks because atmospheric CO_2 becomes locked in their tissues and is returned to the atmosphere only when the tree decays. Larger trees also sequester more carbon due to their increased foliage biomass acting as greater carbon stores than young trees [7,69]. Studying the carbon sequestration patterns and biomass is important to determine the correct policies to maximize the amount of carbon being sequestered in urban settings.

7. Assessment of carbon sequestration

Multitude of natural phenomena, include oceanic, geological and chemical processes happen on Earth contributing to sequestration of atmospheric CO_2 in various natural sinks and also managed globally as carbon cycle in the urban ecosystem [70]. Trees are capable of effective sequestration and storage of atmospheric carbon in above-ground and below-ground biomass by way of processes of photosynthesis and tree growth. Carbon is absorbed and assimilated by tree foliage and is stored as carbon-rich organic compounds such as cellulose and hemicelluloses, lignin, starch, lipid and waxes, mostly in secondary woody tissues in tree boles and in large roots, as well as in foliage, branches and roots [71,72]. In addition, Lal [27] has underscored the significance of sequestration through soils-vegetation-forests-wetlands while discussing different scenarios for terrestrial sequestration.

Biomass is an essential aspect of studies related to carbon sequestration [73]. During recent past decades, the amount of carbon stored in the biomass has gained special attention as a result of efforts of the UN Framework Convention on Climate Change (UNFCCC). There exist direct and indirect methods to calculate terrestrial biomass [74,75]. Direct methods, also known as destructive methods, involve felling of trees to determine biomass which is accurate but not feasible in the current situation. Indirect methods use measurable parameters for estimation of stand biomass based on allometric equations. All stand biomass estimating methods need to involve a prediction of individual tree biomass and summation of these quantities for the purpose of obtaining per-hectare stand biomass, at least in their developmental stages [76]. The use of circumference or girth at breast height (GBH) alone expressing the basal area for above-ground biomass estimation is common to many studies demonstrating diameter at breast height (dbh) along with tree height as two important biophysical measurements measuring for each tree sample as universally used main factors [53,62] because it shows a high correlation with all tree biomass components and easy to obtain accurately [77].

Another method for determining biomass of live vegetations is based on the use of aerial surveys of forest cover. Recently, the use of remote sensing in estimating biomass density of forests has been investigated. Even remote sensing techniques require ground data at landscape levels for calibration and ground verification because remote sensing techniques do not measure biomass. They rather measure some other forest characteristics, for e.g. crown reactivity or brightness. Studies such as [78,79] can be helpful to make inferences about larger populations. The increasing importance of forestry-based carbon sequestration assessment in monitoring the carbon cycle at the global level has led to requirement of robust techniques for rapid information retrieval. By virtue of being essential and common, these advanced techniques may be widely applied for estimation, future prediction and management of terrestrial carbon sequestration. Geographic Information Systems (GIS) helps in managing urban areas [80] and forestry projects efficiently reducing management costs and creating common database of diverse types of data for intelligent planning [81].

8. Urban forests: costs, services and issues

Human populations are directly affected by trees which change the socio-economic, health, and aesthetic aspects of the environment with the prominently visible effect on urban areas because of the higher concentration of humans, elaborates Nowak [9]. He further adds that the urban forests known to be comprised all the trees within the urban lands also include different ecosystem components accompanying these trees, including but not limited to soils, understory flora etc., despite lack of their explicit identification. Similar to the rural settings, the urban forests can possess forested stands-in addition to the trees along streets, in parks, in residential areas, and various land uses- demonstrating a mix of naturally regenerated as well as planted trees. Their prominent attributes are greater proximity to densely concentrated or large human populations, higher diversity of forest patch structures and species, management more focused on the sustenance of the health of the trees/ecosystem services, and multiple types of ownership (public and private). Nowak [82] informs that the trees in urban areas including a mix of naturally regenerated and planted species require their management for the purpose of sustaining the health and benefits of the trees and reducing the risks which human population may come across in addition to the avoidable conflicts. The issues apart from the management costs associated with urban forests include existence of multiple risks such as human injury, damages to urban property, power outages etc. due to the falling of trees and limbs posing additional costs which can be reduced with the help of proper management which can give rise to plethora of benefits not only for this but for future generations also. Similarly, disposing of leaves and different detritus, despite requiring significant costs, offers huge potentialities as regards valuable wood or organic matter supply.

Nowak and Dwyer [83] posit that trees in the urban areas offer huge annual ecosystem services influencing the local physical and social environment, and therefore influence the quality of life for urban population which come at a cost which mainly include conservation of energy, CO_2 sequestration, hydrology, reduction of noise, quality of air and life, well being of the communities, physical/mental health, and economic development in the local areas. Nowak [82] underscores the powerfulness of the natural regeneration in giving shape to urban forests. However, Nowak [9] argues that planting of trees and other multitude of maintenance activities demand incurrence of economic costs for healthy and safe urban forests, also emphasizing the involvement of additional economic and environmental costs in improving tree cover tending to be precipitation restricted. Further, he clarifies that plantation of the trees in urban settings offers huge benefits for the population in urban areas which often needs scarce resources such as water as well as economic resources.

Forests and non forested stocks release CO_2 through natural processes [84] and natural or planted vegetations help in improving land cover in agricultural fields and adding carbon inputs to soil. Climate change and the resulting global warming owing to emissions are causing significant environmental and atmospheric degradations. Urban forests play an important role in ecosystem services of humans in many ways in addition to filtering air-water-sunlight and providing shelter to animals and recreational areas for humans, by moderating local climate by means of slowing wind and storm water, shading homes and businesses to conserve energy, and by being critical in cooling the urban heating effect thereby potentially reducing their impact in plaguing cities during peak summer [9,83]. Despite affecting climate change, urban forests are often disregarded because of lower understanding and lesser quantification of their ecosystem services. To make more sustainable cities in future, ecological disturbances need to be managed and minimized keeping in view the significance of urban trees in storing and sequestering carbon in addition to their aesthetic contribution, scenic beauty and other incomparable benefits [7]. The salient benefits of the urban forests are presented in Table 1.

Table 1. Benefits of urban forests

	Benefits	Studies
1.	Noise pollution reduction	[17,83,85,86]
2.	Pollution mitigation	[17,83,86–88]
3.	Urban climate extremes amelioration	[9,17,83,89]
4.	Urban heat islands mitigation	[36,90]
5.	Outdoor recreation and enjoyment	[83,86,91,92]
6.	Aesthetic contribution/Scenic beauty/Visual amenity	[83,93–95]
7.	Water quality improvement	[86,96,97]
8.	Air quality improvement	[9,31,86]
9.	Consumption of electricity for heating and cooling reduction	[9,15,83]
10.	New power utilities investments reduction	[98]
11.	Urban glare and reflection Control	[52,83]
12.	General livability and quality of urban life improvement	[9,17,96]
13.	Tourism boost	[99]
14.	Carbon storage and sequestration	[60,100]
15.	Birds and other wildlife attraction	[101,102]
16.	Specialty timbers source	[103]
17.	Urban hydrology	[9,83]
18.	Human health contribution/Relaxation/Stress-anxiety levels reduction	[9,83,104,105]

Nowak [106], however, reminds to give attention to the effect of Insects, Diseases, Wildfire, Storms, Invasive plants, Development, Pollution, Climate change, Improper management etc. on urban forests as potential threats which can change the urban forests and their benefits. Figure 1 presents the scenes showing different ecological services of urban forests through urban forest at the headquarters campus of IGNOU, New Delhi, India. IGNOU is not only known as a premier institution in open & distance learning (ODL) in the world with maximum enrolments but also has contributed immensely to the government's initiatives related to environment as a responsible educational institution. One such recent initiative is contributions through "One Student One Tree Plantation Drive' where IGNOU with the help of different stakeholders got thousands of trees planted by learners across the country [107].

Figure 1. An urban forest at IGNOU, New Delhi, India depicting some of the ecological services.

9. Urban forests and carbon sequestration

Carbon sequestration is facilitated by all the plant species which contribute in different quantities based on available water, adequate sunlight, and inorganic nutrients [97]. Carbon sequestration, occurring through reforestation of abandoned agricultural and pasture land, is a mitigation measure to control CO_2 and other GHGs in the atmosphere [108]. Urban forests are performing indispensable role in contributing immensely for reducing climate change effects through significant carbon sequestration efficiency in addition to providing plethora of co-benefits in the cities [109]. Nowak [9] underscores the significance of the improved synthesizing and reporting ability and usefulness of the increasing volume of available relevant data for the managers, planners, or policymakers working at different levels and scales. Nowak [9] also emphasizes the significance of the new monitoring programs such as urban FIA monitoring program which integrates data collection with i-Tree variables which makes available the data for analysis by i-Tree and FIA analysis programs both. Anthropogenic influences affect carbon source and sink dynamics [15]. Carbon sequestration, measuring carbon fixation capacity of trees, is one of the judging criteria of ecological benefits also. Urban forests affect local climate, carbon cycles, energy use and climate change [106,110–112]. Urban forests, basically a human-dominated ecosystem, are critical for the planet. A study [113] attempting to address the issue of micro-climatic variations due to changing land-cover in the Kuwait used the Landsat image of 1989, 1991 and 2000 for computation of surface temperature and land-cover classification to understand the relationship between micro-climate and land-cover with the results showing increased temperatures over the built-up areas and hydrocarbon contaminated surface, and an incremental trend since 1980s in the long term temperature trend in the area increasing sharply in post-1990s, probably on account of cumulative effect of urban-industrial development, hydrocarbon pollution, and increased carbon emission.

According to a study [114], educational level and environmental awareness of urban residents are decisive for the existence and management of the green spaces as their perceptions on the greenery are significant for urban greenery development. The system of declaring a city as "Tree City USA" in the USA, and as "National Garden City" in China were, for example, utilized based on the basic criteria viz. per-capita-green space, green space-to-land ratio, green space canopy coverage ratio to accord these recognitions to cities in these countries which recognized over 3000 cities-towns-communities as "Tree City USA" and over 100 cities as "National Garden City". The "Urban Green Model" in Singapore is also a similar and worth emulating scheme. India is also active in such projects of educating its population and policy makers of the benefits of urban green spaces given that public knowledge along with its connection between human wellbeing and ecosystem services is limited.

There is a need to undertake plantations in urban areas in parks-residential areas—street-road avenues-industrial sites as shelter-belts plantation as they act as efficient filters of airborne particles by virtue of their large size-high surface to volume ratio of foliage--hairy or rough leaf and bark surfaces, and cleanse the airborne particulate pollution in environment also being beneficial in other important ecosystem services [115], e.g. extending help in achieving Sustainable Development Goals (SDGs) & Nationally Determined Contributions (NDCs), and contributing in carbon storage and sequestration in urban society. Urban forests also remove large amounts of air pollutants consequently improving air quality. Further, it is notable that the management of trees and evaluation of potential problems connected to their presence in the urban environment involve a series of actions linked to the knowledge of plant placement; to the analysis of health and stability of trees allowing the planning of essential interventions not only for their care but for limiting the risks of unexpected fall also [116].

Global phenomenon of urbanization arising from development has severely affected the urban areas of India, too [117]. Considering the harmful effects of increased carbon emissions reminds the urgent need for the planning of total geographical area under urban forests and tree cover whose management seeks the main effort to negate the environmental damages. Mini forests maintained by government agencies and big green fragmented areas which are non-forested but are tree dominated also are urban forests, in addition to some more extended green areas recognized as patches including trees in parks-within the premises of historical monuments-gardens-avenues-university/institute campuses-landscapes-areas-places of beautification which are recognized for their social-cultural-aesthetic values and tribal importance, for e.g. in Arunachal Pradesh (India) parting a potent to biodiversity hotspot [118] is also helpful in carbon sequestration [119]. These arguments receive ample support from a recent study [117] conducted in Delhi (India) focused on evaluating the role of such scattered green areas in decreasing GHGs effects and carbon mitigation while making an assessment of the potential of urban trees of storing good amount of carbon in the form of its standing biomass. Another example of urban forest significance was showcased in a study [72] based on the importance of dominant campus trees of St. Mary's College of Thoothukudi, Tamilnadu (India) focusing on applying the approach of urban tree management to measure carbon sequestered by urban trees in quantifying organic carbon by nondestructive method determining carbon stock for as many as 219 tree species with the dominance of *Polyalthia longifolia*, *Azadirachta indica* and *Cocos nucifera* species.

This is therefore underscored that the need to maximize the advantages of urban forests, opting suitable management and maintenance is critical which provide multiple benefits, necessary to maintain rich species diversity and sustainability [120] despite substantial logistical and social obstacles associated with the research in urban areas which might be the possible reasons separately or jointly behind limited experimental studies focused on urban forests so far.

10. Discussions and conclusion

Nowak [9] emphasizes the huge effect of urban forests on the routine life of human populations informing at the same time that the population in the U.S. in excess of 80 percent of lives in urban areas. The findings of the study in line with the primary motivations of conducting this study underscore the paucity of relevant studies related to urban forests which play significant role in mitigating the negative consequences of climate change at a very crucial time when governments are putting in their best efforts to meet international goals and commitments such as SDGs and NDCs amidst the trend of unplanned growth of urban population remarkably faster than rural population across the globe. The emphasis of various studies undertaken in the past has been on the environmental, sustainable and economic benefits from urban forests conducted in the context of different categories of countries. Estimation of this carbon content both in vegetations and in soil becomes imperative to assess the carbon sequestration potential referred to as terrestrial sequestration. Trees have been helping mankind from various significant aspects including but not limited to sequestering activities as per the vital assessment done for countries -like the US, China, India and Singapore -to promote urban forestry agenda. Big trees deplete more air pollution and carbon capture or store than small trees annually [33]. With the huge increase of urbanization across the globe, it is becoming important to evaluate carbon dynamics in the urban systems. The need is to understand and fill the gaps to understand the variability and range of various carbon sinks for the potential associated with using other methods along with allometric relationships developed outside of urban environments [37]. Methodological standardization and implementation of averaged equations across cities could be one potential solution for variability reduction. In the meantime, a properly defined institutional mechanism and strong legal framework for implementing urban forestry are crucial for cities not only aesthetically but also functionally helping in making cities agreeable places to live in and work at.

Studies with respect to carbon sequestration in trees have gained traction in recent times given that trees play crucial role in the recycling of air in the lower atmosphere. Forests and non forested stocks release CO_2 through natural processes [84] and further the natural or planted vegetation help in improving land cover in agricultural fields and adding carbon inputs to the soil. Studies have emphasized on the need of conducting future studies focused on tree dominated urban areas such as institutions' campuses, avenues, streets and public parks and their roles in carbon sequestration. Past studies also underscored the need to know the potentials of CO_2 sequestration from the selected tree species through biomass estimation [121]. Apart from forests, role of the urban forests related with carbon sequestration encourages for the evaluation of the amount of carbon loss and capture, and for the estimation of urban forests' carbon pool as estimation of biomass has been found to be necessary. The review reveals that studies have been conducted to estimate urban forest biomass to evaluate their carbon stocks but there is further need to explore concrete methods and strategies to quantify and estimate the biomass of urban forests and their carbon sequestration potential more accurately [122].

In order to mitigate GHGs emissions leading to global warming, irreversible natural degradations and severe consequences, carbon sequestration is being construed as a feasible approach. Nonetheless, despite it seems to be promising, its commercial application is yet to be ascertained in terms of carbon credits, carbon trading, and carbon market the success of which would be subject to overcoming the challenges of developing international regulatory framework helpful in deciding its viability on the basis of a long-term lifecycle assessment. It is notable that urban forests in the urban areas are affected by urbanization. Their protection is feasible on the basis of assessment of their values, documentation and accounting for the purpose of combating the negative impacts of urbanization. Some of the salient significance of the green covers in the urban areas include energy conservation, urban heat island reduction, noise and air pollution reduction, carbon sequestration, aesthetics, recreations among others and these values and associated concerns need urgent requirement of development of addressing methods with the mandatory compliance stipulations for the planners in order to maintain and enforce the prescribed norms or laws related to green covers. In this regard, ample assistance should be sought out from the norms related to tree cover advocated in different developed countries to implement them in promising countries like India for desired level of achievements in years to come.

This review paper finds that previous scientific studies have explored and comprehended the issues related to the aboveground biomass and carbon stock from urban forests finding the biomass and carbon stock estimation methods classified as destructive approach not practically considered now, and non-destructive approach dependent on the measurable parameters and also on remote sensing data requiring further field validations. The review also reveals that due to insufficient estimation on account of variations and variability in different countries, the future enquiry needs to be based on the development of specific equations in view of difference in habitats and urban forests degradations conditions. The paper, having discussed the issues and management costs associated with urban forests also in addition to the benefits of urban forests contextualizing the developing countries more particularly, highlighting the significance of urban forests in different era offers suitable advices, and has the potential to be useful for policymakers and urban planners in addition to researchers and academia engaged in the field of climate change mitigation.

Conflict of interest

The authors declare no conflict of interest.

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