Rodriguez Franco *et al. Carbon Footprints* 2023;2:18
DOI: 10.20517/cf.2023.35

Carbon Footprints

Review

Open Access

Decreasing the urban carbon footprint with woody biomass biochar in the United States of America

Carlos Rodriguez Franco[1], **Deborah S. Page-Dumroese**[2]

[1]U.S. Department of Agriculture, Forest Service, Washington Office. Research and Development, Washington, DC 20250, USA.
[2]U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Moscow, ID 83843 USA.

Correspondence to: Dr. Carlos Rodriguez Franco, U.S. Department of Agriculture, Forest Service, Washington Office, Research and Development, 201, 14th Street, S.W., 2 NW Washington, DC 20250, USA. E-mail: carlos.rodriguez-franco@usda.gov

How to cite this article: Rodriguez Franco C, Page-Dumroese DS. Decreasing the urban carbon footprint with woody biomass biochar in the united states of america. *Carbon Footprints* 2023;2:18. https://dx.doi.org/10.20517/cf.2023.35

Received: 21 Jun 2023 **First Decision:** 8 Aug 2023 **Revised:** 21 Aug 2023 **Accepted:** 5 Sep 2023 **Published:** 12 Sep 2023

Academic Editor: Jingzheng Ren **Copy Editor:** Fangyuan Liu **Production Editor:** Fangyuan Liu

Abstract

Urban centers are places with a high human population concentration, and they can pose social, economic, and environmental challenges. These challenges are accentuated by the increased use of available open space for housing and industrial expansion, leading to elevated energy consumption, increased pollution, higher carbon emissions, and, consequently, adverse effects on human health. Many of these issues also contribute to the acceleration of climate change. There are several ways to decrease these problems through the expansion of greenspaces that conserve biodiversity, decrease air pollution, improve human well-being, and reduce human health risks, while also allowing people to enjoy the benefits of ecosystem services. This review is aimed at professionals who can manage urban landscapes - including adjacent forests, urban parks, tree beds, or home gardens that produce biomass that, together with other non-chemically treated wood waste, could be used to produce and use biochar. Biochar-amended soils provide the benefits of increased carbon sequestration, water retention, and soil productivity and can also decrease stormwater runoff. In addition, a small number of cities around the world have adopted biochar as a nature-based solution to decrease the impacts of climate change. We point out the opportunities and benefits of converting urban wood waste into biochar, how cities can improve their green environments, and, at the same time, produce energy from waste that would otherwise end in landfills with no use or value. Finally, based on previous assessments of wood waste in the United States of America, we estimate the biochar potential to sequester CO_2.

Keywords: Biochar, carbon sequestration, urban forests, cities, wood waste, climate change

INTRODUCTION

Now more than ever, it is essential to underscore the importance of climate change impacts (e.g., intensive and semi-permanent droughts, hurricanes, snowstorms, and other climate disturbances) and their relationship with urban environments and human populations. For example, severe wildfires in Lahaina, Hawaii, California, Washington State, Oregon, and outside of the USA, Greece, Portugal, and Spain have destroyed cities, livelihoods, and lives. However, urban forests constitute a green space that provides many benefits, including mitigation of some of those impacts. The importance of managing forests and using the generated forest residues to produce biochar can also increase other benefits such as carbon sequestration and avoided emissions when those residues are either landfilled or open burned. Today, urban populations are experiencing unprecedented levels of density, with a continuous influx of people into major cities driven by global population growth. In 2022, the worldwide population reached 8.0 billion people, growing from an estimated 2.5 billion people in 1950. Current population projections indicate that the world population will surpass 10 billion by 2059[1]. According to the United Nations[2], urbanization is the outcome of intricate socio-economic processes that transform the environment and reshape the spatial distribution of populations, which alters demographics and social structures of rural and urban areas. From 1950 to 2018, the proportion of the global population living in urban areas rose significantly, climbing from 30%-50%, and this figure is expected to reach 68% by 2050. Currently, nearly half of the world's urban population resides in areas with fewer than 500,000 inhabitants, while roughly one in eight individuals live in the 33 megacities, each boasting a population of over 10 million residents. Looking ahead to 2030, the world is projected to be home to 43 megacities, mostly in developing regions[2].

In the last three centuries, the United States of America (USA) has undergone rapid urbanization and industrialization[3]. Worldwide, urbanization is attributed to several technological advances that fostered industrial development and increased the need for workers to be closer to factories that are generally built in and around cities. The most influential technological innovations promoting urbanization at the beginning of the century were electric lighting, communication improvements, intracity transportation, and the rise of skyscrapers[4]. Today, the USA has 333 million inhabitants and is the third most populated country in the world[5], with more than 75% of the population living in urban areas[6].

Global climate change is currently affecting urban ecosystems and will persist in doing so. Consequently, there is an imperative to work on potential solutions for climate change mitigation to enhance the prospects for creating sustainable urban environments in the future. Green infrastructure provides a range of ecosystem services, such as decreasing air pollution and stormwater runoff while increasing carbon sequestration. Other climate change benefits associated with green infrastructure include clean water and biodiversity conservation. Urban tree removals, plus dead and dying trees, are a source of biomass that generally goes to landfills or is burned. Some large wood left on-site can help support ecological functions, but a balance must be struck between micro- and macro-fauna habitat and carbon sequestration with fire management. Large wood can serve as a carbon sequestration strategy as it effectively mitigates carbon emissions; this approach is incorporated into many urban forest management plans across the USA, for example, the city of Somerville, Massachusetts[7]. However, in many locations, there exists a substantial quantity of dead wood resulting from hurricanes, insects, diseases, or overstocked stands; therefore, removal or open burning is often used to dispose of the excess.

In some cities, excess wood is used as firewood or chipped for landscape mulch. Converting urban wood waste into biochar is one method that can provide an opportunity for cities to simultaneously improve city environments, benefit from alternative energy production, and keep woody material out of landfills with no added ecosystem services. Biochar can also be one more tool in the strategy for carbon sequestration and negative emissions technologies to decrease the climate change impacts[8]. Nowadays, amidst the growing importance of green infrastructure and its capability to enhance carbon sequestration, there remains an underexplored avenue in the realm of negative emission technologies, such as the application of biochar for energy production and soil amendment in urban environments, which holds promise for mitigating the impacts of climate change.

The main objective of this paper is to conduct a systematic literature review with a focus on potential uses of urban vegetation residual biomass for biochar production in the USA. We also highlight opportunities, benefits and research needs regarding how cities can improve their green environments while also producing bioenergy from urban woody biomass that would otherwise be disposed of in landfills with no use or value.

URBAN ENVIRONMENTS AND CLIMATE CHANGE

Urban areas account for approximately 75% of the total carbon dioxide emissions around the world. They cover about 2% of the earth's land surface and host more than half of the global population[9]. Most carbon emissions generated from urban settlements also contribute to climate change, thereby increasingly exposing the infrastructure, people, and businesses to the impacts of climate-related hazards, particularly in larger cities. It is without a doubt that climate change affects urban environments and can alter the health and survival of urban vegetation, people, and ecosystem services (e.g., clean water, stormwater runoff, air pollution control). Anthropogenic emissions are believed to contribute to severe weather events, and in the USA alone, approximately 40% of the population lives near coastal areas that are increasingly vulnerable to the devastating impacts of a changing climate[10].

A large number of people concentrated in a small land area can cause several environmental problems. For example, air and water pollution, heat island effects creating microclimates, solid waste disposal, air quality, haze, carbon emissions, and heat discomfort are just a few of the environmental pressures in large urban areas[11]. Singh *et al.* have indicated that widespread growth in the human population, fast urbanization, and climate change with extreme weather conditions are the three main challenges the world is facing today[12]. In particular, rapid urbanization affects land use and waste generation, accelerating the processes responsible for global climate change.

It is evident that human activities have led to a rise in greenhouse gas (GHG) concentrations since 1750, causing an increase in global surface temperature. From 1850 to 2019, the temperature rose by approximately 1.07 °C[13]. Greenhouse gas concentrations have continued to increase in the atmosphere, reaching an annual average of 410 ppm of carbon dioxide. Increased carbon dioxide and temperature have cumulative effects that exacerbate climate change. For example, 2021 was the sixth warmest year worldwide, with a temperature that was 0.84 °C (1.51 °F) above the 20th century average[14].

In the USA, urban areas can be defined as metropolitan and micropolitan statistical areas that are densely developed and encompass residential, commercial, and other nonresidential urban land uses[15]. Changing demographics and urban area size have significantly influenced the environmental structure of different regions in the USA over the past two centuries[16]. Currently, the cities with the highest density of population are concentrated along the eastern coast, specifically in cities such as Jersey City, and New York City in the New York State. Notably, nine of the ten most densely populated urban areas are located in the western USA[17].

A changing climate is responsible for an increase in natural disturbances. For example, in 2021, the USA had 20 distinct billion-dollar weather- and climate-related disasters. The cost of these disasters totaled approximately $145 billion. In addition, 2021 marked yet another year of costly, frequent, and diverse extreme climatic events in the USA, which impacted thousands of people's lives and livelihoods. These impacts include both direct and indirect fatalities, with many affected populations residing in vulnerable coastal areas, at the wildland-urban interface, or in river floodplains[18].

Climate change impacts on urban environments range from decreased ecosystem service availability, heightened intensity and frequency of extreme events such as floods and droughts, wildfires, insects, diseases, and health problems, and exacerbation of urban heat islands[19,20]. During the last 10 years, 90% of the USA counties have experienced a climate disaster requiring federal assistance for recovery. Some counties had 12 disasters in 2021 alone[21,22].

The negative impacts of a changing climate decrease the quality of life, biodiversity, and environmental sustainability[23]. Some of the ecological problems related to human well-being, pollution, quality of life, and biodiversity could be solved, in part, by maintaining and increasing greenspaces (e.g., forests, meadows, wetlands, water bodies) which can also increase the resilience and sustainability of urban environments. The World Health Organization[24] has indicated that urban greenspaces play a vital role in conserving the health and well-being of the population in cities, and providing ecosystem services and ecological benefits that improve air quality, regulate microclimates, and generally beautify the urban landscape. Furthermore, these greenspaces contribute to many recreational, social, and cultural values[25,26].

The environmental problems associated with a changing climate are mounting. To mitigate these impacts, several cities are developing a range of nature-based solutions (NBS) to partner with urban tree planting initiatives. These efforts aim to expand both the quantity and diversity of vegetated surfaces while enhancing soil permeability[27]. This strategy promotes the development of urban green infrastructure that bolsters city resilience, supporting adaptability to challenges such as overheating, flooding, air pollution, health and well-being, as well as reducing biodiversity loss[28]. According to Raymond *et al.* (2017), NBS bring together established ecosystem-based approaches that are being more recognized as foundations to advance towards sustainable development in urban areas[29].

IMPORTANCE OF URBAN FORESTS

In general, urban forests include all trees growing within the urban area and could include street trees, yards, and parks. As such, urban forests can be seen as a gradient that connects different shapes and areas of land in a specific area[10,30]. Following this definition, USA urban forests cover 141 million acres. In addition, the U.S. Department of Agriculture, Forest Service notes that almost 60 National Forests and Grasslands are surrounded by populations of 1 million or more and can also be considered urban national forests. If the criteria for population access to national forests is expanded to include individuals living within an 80-kilometer radius of a national forest, an additional 153 million people would have proximity to urban forests[31].

Urban forests improve human health, strengthen social connections, and add economic value to communities. Similar to other forested ecosystems, urban forests provide services that are (1) *provisioning services* such as food, water, clean air, wood, grasslands (open space), and fiber; (2) *regulating services* that affect climate, floods, disease, wastes, and water quality and quantity; (3) *cultural services* that provide recreational, aesthetic, and spiritual benefits; and (4) *supporting services* such as soil formation, photosynthesis, and nutrient cycling[30,32]. In addition, urban forests are known for their contribution to maintain biodiversity and mitigate the impacts of climate change in cities through carbon sequestration[33].

Trees and the pervious soil in which they grow can reduce stormwater runoff and improve water quality by decreasing runoff volume and the concentration of pollutants[34]. However, urban tree planting efforts are limited in scope and are unlikely to fully counterbalance the urban GHG emissions and atmospheric pollution generated by modern cities[35]. Nevertheless, trees do have localized effects on climate, thermal comfort, human health, and habitat for other species. These efforts can be impactful when considered at a smaller, site-specific scale. Scientists have described the additional benefits of urban forests. For example, in Taipei, Taiwan, green structures reduced the effects of air pollution and heat on deaths from cardiovascular disease[36]; similarly, in Canada, an increase in greenness around residential areas resulted in a reduction in the risk of dying from some common causes[37]. There are a host of other benefits from increased tree cover in urban areas, including reducing both non-accidental and cardiovascular mortality[38]. These reductions vary considerably across the USA and depend on demographics, age distribution, the quality and availability of health care, and other factors[39]. In general, there is increased public recognition that urban trees are an essential component of health-supportive environments, and that exposure to trees can provide many health benefits[40]. In addition to physical health, urban trees also promote emotional health and social interactions[41].

There are also economic benefits associated with urban forests. The total benefit (i.e., environmental, economic, and social benefits) of urban forests is estimated to be £4.9 bn per year in the United Kingdom, with the value of urban woodland and trees to air pollution absorption (social "passive use") estimated to be about £0.2 bn per year[42]. In the USA, Nowak and Greenfield[43] estimated that urban forests provide annual benefits totaling $18.3 billion, which encompass air pollution removal, increased carbon sequestration, decreased building energy use, and the avoidance of pollution emissions. These economic benefits are additive to human health and social benefits.

BIOCHAR PRODUCTION TECHNOLOGIES FOR URBAN ENVIRONMENTS

Biochar is biomass-derived charcoal that is intended to be applied to the soil alone or mixed with compost. It is usually highly porous and has a high carbon content[44-47]. Biochar is also defined as the solid residue remaining after the thermo-chemical transformation of biomass with the intent of carbon sequestration[48]. The production of biochar is similar to charcoal production. Previously, "biochar" or charcoal was produced by slowly burning wood in a shallow pit covered with soil. Modern technologies have generally replaced pit kilns, and there are numerous methods that create high-quality biochar. For example, kilns of various construction materials or retorts (airtight vessels to create biochar in batches), which can be manually- or computer-controlled, are small-scale, in-place methods to produce biochar. Large-scale production of biochar incorporates the ability to capture heat and/or synthetic gas for electrical power generation or process heat, while moderate-scale production systems include air curtain burners that create biochar in batches or continuously. Moderate-scale production is often conducted either near where the woody biomass is created or at a landfill to keep the biomass out of the waste stream. All of these methods can be significantly less polluting than open burning of waste wood[49,50] and reduce loads at landfills [Table 1].

The conditions that create biochar transform recently dead vegetative biomass into a more stable form of carbon. The conversion process releases more energy than it consumes, and depending on the conversion methods, bioenergy can be used to generate syngas, electricity, or heat[51,52] [Table 2]. Converting biomass into energy involves biochemical and thermochemical processes. Thermochemical processes include gasification, pyrolysis, liquefaction, and direct combustion[58,59]. Pyrolysis is considered the most consistent

Table 1. Examples of biochar production technologies with different levels of complexity and costs[a]

Equipment	Technology level[b]	Complexity of operation[c]	Biochar particle size output[d]	By-products	Labor needed[e]	Production equipment cost[f]	Air emissions[g]
Pit, mound, and brick kilns	Low	Simple	Large	None	Low	Low	High
Metal kilns	Low to medium	Simple	Large to Medium	None	Low	Low	High
Flame cap kilns	Low	Simple	Large	None	Low	Low	Low
Mobile systems	Medium	Medium	Medium	None	Low	Medium	Low
Modular	Medium	Medium to High	Small	From none to many and heat used for greenhouses or local heating networks and process heat (hot water). Gas for energy	Medium	Medium to high	Low
Biomass boilers	High	High	Small	Heat and hot water, combined heat and power	High	Medium to high	Low
Small-scale combined heat and biochar urban soils	High	High	Small	Power and heat	Low	Medium	Low
Small-scale combined heat and Biochar for buildings	High	High	Small	Heat	Low	Low	Low

[a]Adapted from[50]. [b]Low level does not require specialized labor, only a construction worker; Medium requires a technician to assemble the equipment; High requires specialized labor to conduct the work. [c]Simple indicates a flow work involving no high technology management; Medium requires engine operation management experience; High requires highly specialized labor for the operation of the equipment and production system. [d]Particle size output is referred to biochar final product size and shape irregularity. Large shows high heterogeneity in size (more than 50 mm long) and shape; Medium is a mix of heterogeneity and more homogeneous shape and size (between 20 mm to 50 mm long) and more square to round shape; Small is more homogeneous material in size (less than 20 mm to powder) and shape. [e]Labor: Low crew size from 1 to 3 people; Medium from 2 to 6 people; High more than 10 people. [f]Cost: Low range from less than $5,000.00 to $100,000.00; Medium from $200,000.00 to $750,000.00; and High from $1,000,000 and above. Costs are based on information from[51]. [g]Based on information from the comparison of criteria emissions from biomass management options[52].

Table 2. Potential feedstock biomass and biochar production for four of the Carbon Neutral Cities Alliance

City	Feedstock or biochar (metric tons)						
	Garden waste	Demolition wood waste	Sewage and sludge	Food waste	Current biochar production	Calculated potential biochar production*	Source
Stockholm	9,700 - 10,000	19,887	77,600	100,000	300	17,060	[53,54]
Helsinki	20,000 - 38,500	40,000 - 60, 000	70,000 - 90,000	60,000 - 80,000	3,000 (sludge feedstock-based biochar)	37,500 - 50,700	[55]
Boulder	9,041	-	-	-	30	1,356	[56]
Minneapolis	4,481	-	-	-	Testing equipment for production	1,120	[57]

*Estimates given by the references cited by each city.

process to convert biomass because it is possible to manipulate the proportions of the main products (i.e., pyrolytic oils with a high energy density, the biochar with key properties for soil amendment, or the gas to produce energy) by controlling the main reaction parameters of temperature, rate of heating, and vapor residence time[45,46,60].

Biochar can be produced by conventional carbonization or slow pyrolysis, fast pyrolysis, and flash carbonization[47]. Slow pyrolysis has the advantage that can retain up to 50% of the feedstock carbon in stable biochar. It is important to know that, although the systems of biomass conversion to biochar are well-known, the type of biomass, temperature, heating rate, residence time, and pressure influence biochar production rate and its chemical and physical properties[45,61]. Biochar production in urban environments is scalable [Table 3], and depending on the amount of material, the available work force, and the local operating conditions, different systems can be used. Slash piles are best used in larger forested areas. Kilns of various sizes are good tools for forest restoration activities because they can use volunteer crews or conservation crews to load, quench, and apply biochar[62,63]. The operation of an air curtain burner-type system is beneficial for sensitive watersheds. These systems also require a small crew capable of continuously producing biochar. All systems, including pile burning, can emit less smoke and cause fewer adverse impacts on soil resources. In China, the Center of Biochar and Green Agriculture of Nanjing Agricultural University started work in 2009 to develop a biochar network of field trials with rice-, maize-, wheat- and cotton-feedstock biochar across a number of locations. This Center studies biochar effects on soil fertility and crop productivity, greenhouse gas emissions, soil moisture preservation, and soil pollution control[64]. The Center has been very active in innovating new biochar production systems in cooperation with China's manufacturing biochar equipment producers. The biochar production systems developed in China have the potential to be used in urban environments; these systems encompass various technologies, such as smart straw pelleting machines, smart mobile pyrolyzers, truck-driven mobile pyrolyzers, and mobile pilot scale pyrolizers. Each of these methods boasts different production capacities[64,65].

Since urban forests can include national forests near urban centers, biochar production and use can provide numerous benefits for both urban and natural forests. We have mentioned climate change mitigation as one key benefit. Perhaps at this moment, climate change mitigation is the most important aspect of biochar's capacity as it can increase soil carbon[49]. Biochar production also reduces wildfire risk and improves soil health by increasing soil pH and water retention. It can also absorb heavy metals, which is important for brown-field or other contaminated soil remediation. Changing agricultural, natural forest, or urban forest harvest and biomass disposal methods can improve above- and below-ground carbon storage by converting biomass normally burned or discarded in landfills to biochar[66]. Importantly, using biochar provides a pathway to restore soil organic carbon, increase soil organic matter, and reduce costs associated with biomass disposal.

During pyrolysis, the conversion rate of biomass to biochar depends on technology, temperature, and residence times. It is usually considered to range from 20% to 40% by mass[67]. Similarly, the biochar created using a variety of methods has a carbon concentration ranging from 25% to 90% (this is my data - no need to cite). Producing biochar with pyrolysis units under controlled environments results in biochar and energy production coupled with decreased emissions[68]. If woody biomass is open burned or left to decompose, the carbon contained within that biomass is released into the atmosphere immediately (with burning) or over a longer period of time (decomposition)[69]. However, when woody biomass is pyrolyzed, only about half of the plant carbon is volatilized. The remaining half of the carbon is converted into biochar that degrades extremely slowly (decades to centuries) under natural conditions[69].

Biochar uses in carbon-neutral cities

Many cities are striving to become climate-neutral in the coming years because of the changing physical environment and risks to ecological infrastructure, human health, and other climate-induced problems such as flooding, air pollution, water scarcity, and droughts. Further, climate change more severely impacts low-income groups and other vulnerable populations[70]. Biochar production is a ready-to-implement technology that could be carbon-negative[71] and promote nature-based solutions for adaptation and mitigation of climate change impacts. Nature-based solutions can be cost-effective in many urban areas and can also result in building ecosystem resilience[29].

Table 3. Examples of different scales and costs of biochar production in urban settings in the USA

Production method	Type of material	Cost (USD)	Method constraints
Slash piles or conservation burns[a] 	Any woody residues of any size are used Wood is loosely staked, and ideally, the piles are top-lit to develop a flame cap to reduce smoke	$1,000-2,000 per acre	Burning piles can impact the soil Opportunity for escaped fire. Coals must be raked out when flames subside.
Ring of Fire Kiln[b] 	Woody residues generally < 15 cm in diameter and cut to fit the kiln Biochar created in batches. Two batches per day	Kiln is $2,000 Labor can be from conservation crews	Wood must be cut to fit the kiln Coals are quenched when kiln is full, which requires ~ less than 400 liters of water for each batch
Big Box Kiln[c] 	Woody residues up to 60 cm in diameter and 3 m long Biochar created in batches Two batches per day	Kiln cost is ~$12,000 Labor can be volunteer or contracted	Can be hand-loaded, but a mini-excavator is needed for large fuel Coals are quenched when kiln is full of biochar, which requires ~3,000 liters of water for each batch
CharBossb ® air curtain incinerator[d] 	Woody residues up to 60 cm in diameter and 3 m long Biochar created continuously	Equipment cost is ~$150,000 2-3 people required to operate and load equipment	Coals are continually quenched in a water bath, which requires ~200 liters of water each day A mini-excavator is needed to load the larger fuels

[a]Picture Andre Snyder, USDA Forest Service [b] Developed and manufactured by Wilson Biochar (https://wilsonbiochar.com). Picture Carlos Rodriguez Franco, USDA Forest Service. [c] Developed by Dr. Darren McAvoy at Utah State University. Picture Darren McAvoy at Utah State University. [d] Developed and manufactured by Air Burners, Inc. (https://airburners.com). Picture Deb Page-Dumroese, USDA Forest Service.

One of the best current examples of nature-based solutions was initiated by Björn Embrén in 2009 during his employment with the Traffic Administration in Stockholm, Sweden. Embrén developed a tree planting method using biochar, and this initial work has become an example for several cities around the world. Many urban soils are compacted, and this is a major impediment to tree planting and growth. However, successful urban tree plantings can be achieved by increasing soil organic matter and, therefore, soil porosity. This can be achieved through the use of biochar. Other benefits of increased soil porosity are stormwater control, improved water quality, and decreased pollutants in runoff[72,73]. These successes in tree planting with biochar launched the Stockholm Biochar Project with the main aim of using urban green waste to produce biochar and renewable energy. The project was awarded one million Euros from the 2014

Mayors Challenge, which was funded by Bloomberg Philanthropies and EUROCITIES; this funding was used to establish a biochar pilot plant[74]. In 2017, the first large-scale biochar plant was opened in Stockholm to manage the large amounts of green garden and park waste generated by citizens and collected by the city (1,300 metric tons of biomass per year), and produce heat (150 kW) for 80 apartments, and biochar (300 metric tons/year; equivalent to carbon dioxide from 700 cars)[70]. When the project is fully operational with five biochar plants, the expectation is that biochar production will be approximately 7,000 metric tons (m tons), which will sequester 25,200 m tons of carbon dioxide (the equivalent of taking 3,500 cars off the road) and produce 25,200 MW/hour of energy (the equivalent of heat for 400 apartments). The projected estimated revenue for Stockholm is expected to be over $854,000 Euros[75].

Several Swedish cities are moving towards carbon neutrality, aiming to achieve this goal between 2030 and 2050, with plans to continue moving towards being carbon-negative after that[76]. Stockholm, for instance, has adopted a biochar-urban forestry strategy that not only estimates the potential urban feedstock available for biochar production but also explores its use in several applications[54]. As a result, the Stockholm biochar team has published a set of guidelines that can serve as valuable references for other cities seeking to implement similar projects[75]. In Sweden, biochar used in urban forest soil benefits both soil and vegetation growth and survival[77].

According to the Center for Regenerative Solutions[78], a group of European and North American cities (Stockholm, Sweden, Helsinki, Finland, Boulder, Colorado, and Minneapolis, Minnesota), the Urban Sustainability Directors Network, and Carbon Neutral Cities Alliance started a collaboration in 2017 to find solutions that would drawdown atmospheric carbon dioxide while also addressing climate adaptation and social equity. Concurrently, Draper and Smith[79] assessed the biochar feedstock to be used for bioenergy and biochar production for the cities mentioned above. Their findings indicated that the total amount of downed, dead, or removed biomass was not tracked by most cities, with the exception of Stockholm[79], and they also highlighted that the carbon sink potential from biochar in large cities is quite low, with Stockholm being the highest at nearly 4%. The Carbon Neutral Cities Alliance report provided a complete set of recommendations to be considered for these projects and noted that each city should develop its own assessment to have a better perspective on potential biochar feedstock[80]. In addition, the four early-adopter cities listed above have approximately 25,822 m tons of urban tree biomass available each year, which would yield ~17% (4,476 m tons) of it as biochar. This amount is an estimate based on the amount of urban tree biomass in Boulder and Helsinki, tree removal data for Minneapolis, and current biomass collections in Stockholm. The potential production level of biochar, based on available feedstock estimates and calculations made by the authors [Table 2], indicates that in Boulder, Colorado, the impact of biochar on climate change mitigation ranges from 400 to 2,053 m tons of carbon dioxide equivalent reductions per year. In contrast, Helsinki, Finland has a carbon dioxide equivalent reduction that ranges from 18,874 to 46,630 m tons per year. However, when all the feedstocks [Table 2] are considered, the potential CO_2 reductions could reach up to 70,236 m tons of biochar per year[79].

It is worth mentioning that biochar production using wastewater reclamation facility biosolids (sludge) as a feedstock for biochar production is limited, and Helsinki is the only city from this group using it to produce biochar. To meet environmental standards, the first step in treating the biosolids is to use the activated sludge method[79]. Wastewater reclamation facilities in Helsinki adhere to strict environmental standards concerning the amount of nitrogen and phosphorus removed from the wastewater, as the effluent is discharged into the Baltic Sea, which is prone to eutrophication. The high levels of nitrogen and phosphorus removal from the wastewater also lead to similarly high concentrations in the resulting biosolids. One reason for using pyrolysis to create biochar is the ability to decrease pharmaceuticals and other harmful substances, thereby increasing the usefulness of biosolids for biochar production and as a soil amendment.

To move additional cities towards carbon neutrality, data and technologies are available to estimate urban forest vegetation biomass remotely (e.g., LiDAR, satellites), and they are applicable to many different tree species and growth forms. These new technologies improve our estimates of standing tree volume, carbon storage, and the potential biomass available for biochar production[81]. Lan *et al.* have pointed out the importance of converting urban tree waste into valuable products to mitigate climate change impacts and decrease eutrophication[82]. They estimate that in the USA, full utilization of urban tree waste could supply compost, lumber, wood chips, mulch, and biochar and would reduce the annual global warming potential (GWP) by an estimated 127.4 to 251.8 million tons of carbon dioxide equivalent as compared with landfilling. This is attributed to the high eutrophication potential caused by leaf waste and removed trees when they are landfilled; this potential arises due to the release of ammonia, nitrate, and a significant amount of ammonium[82].

Currently, the City of Lincoln, Nebraska[83] is building its first biochar production facility, which is scheduled to be fully operational in the summer of 2023. The University of Nebraska and the Nebraska Forest Service have spent nearly 10 years testing and analyzing the biochar to ensure a quality product. They anticipate that the main uses for biochar will be for public and community tree planting, urban plant beds, parks and turf management, community gardens, and roadside management (filtration of runoff). In addition, biochar could be used in concrete, animal feed, livestock pens, green roofs, living walls, and rain gardens[77,84].

DISCUSSION ABOUT THE POTENTIAL FOR USA URBAN FORESTS TO PRODUCE AND USE BIOCHAR

Similar to other cities around the globe, climate change has impacted USA cities and these changes have resulted in increased tree mortality, susceptibility to insects and diseases, flooding, hurricanes, and other disturbances. For example, the estimation of post-Katrina hurricane vegetation debris volume in the coastal region of Mississippi amounted to 3.4 million cubic meters[85]. Subsequent assessments indicated that urban tree cover has decreased at a rate of approximately 71,000 hectares per year, equivalent to the loss of 36 million trees annually, with an estimated value of $96 million per year[33]. Insects, diseases, windstorms, tornadoes, and other disturbances similarly impact urban vegetation and street trees, which are estimated to cause the mortality of ~1.4 million trees between 2020 and 2050 and cost $30 million per year[86].

Woody biomass is an underutilized resource that is rapidly increasing with greater urbanization. The biomass could be used for a variety of wood products and biochar, and as disturbance events also increase, this is another source of biomass. Disturbances produce urban waste wood that, when transformed into wood products, could result in economic benefits for the city and the owner of the wood. City revenues could help recover the cost of tree removal, replanting, or maintenance of public sites that provide ongoing environmental ecosystem services to society. Nowak *et al.* estimated the potential of urban woody biomass loss in the USA is about 46 million tons of fresh-weight merchantable wood, equivalent to 1.7 billion cubic meters of lumber, or 16 million cords of firewood when assuming an annual mortality rate of 2%[87]. The annual value from urban wood waste ranges between $89-786 million, depending upon the product (e.g., wood chips to lumber). Urban waste wood can be used to produce commercial lumber, which can be further processed into secondary products (e.g., furniture, flooring, pallets, or other by-products), or used to produce bioenergy and biochar. Currently, most of this debris is left to decay, burned in place, or hauled to landfills[88].

The economic and environmental benefits of harnessing urban tree "waste" biomass could be huge; however, progress has been slow. According to Groot *et al.*, USA biochar industry production ranges from 35,000 to 70,000 m tons per year and comes from 135 producers[89]. They also pointed out that there are many factors affecting the development of the market, including technology, quality standards, education and marketing, economics, and widely varying prices and availability[89]. For example, the potential availability of woody biomass in the USA that could be used for biochar production and to increase soil carbon sequestration MacFarlane[90] estimated the amount of biomass generated from urban tree was nearly 22.2 million m tons per year which could supply enough electricity for 2.8 million people per year, or the equivalent of about 72.6 million barrels of oil per year.

One concern that limits greater urban biochar production in the USA centers around policies and regulations. Biochar production and use is greatly affected by air emission policies and regulations, particularly in California, Oregon, and Washington. In these states, local regulatory agencies are issuing official requirements on behalf of the Environmental Protection Agency as a method to enforce the U.S. Clean Air Act of 1963, which provides a federal basis for air quality permitting. State processes are often very detailed and strict, but industrial biochar producers can obtain an operating permit when they comply with all required standards. One confusing aspect is that, although all USA States must follow the Clean Air Act regulations, the permit process could be different for each State[91]. The disparity between local, regional, and national regulations and the overall cost of permitting can discourage potential producers from engaging in this opportunity.

The current estimates of urban tree mortality and removal are on the order of 70 million green m tons of above-ground biomass per year, which is equivalent to 33 million m tons per year on a dry weight basis, when assuming a 2% mortality rate[91]. In addition, another indicator of urban waste wood is the estimation from the Environmental Protection Agency[92] of 18.09 million m tons of woody biomass collected in the USA as Municipal Solid Waste. Of the woody biomass collected in 2018, 17% (3.1 million m tons) was recycled, 8.2% (2.84 million m tons) was used for combustion with energy recovery, and 74.8% (12.15 million m tons) went to the landfill. Nearly all of the woody biomass sent to the landfill has the potential to be used for biochar production. For example, if biochar is produced and used as a long-term method to sequester carbon dioxide and thereby limit carbon emissions from the woody residue left to decompose, 2.5 gigatons of carbon dioxide could be stored in the soil each year and provide a potential global biochar market of $368.85 million by 2028[93].

The concept of a carbon footprint was developed to estimate the amount of greenhouse gas (GHG) emissions to the atmosphere that come from the manufacturing and consumption of goods and services through their supply chain and are expressed in carbon equivalents as a measure of the global warming potential (GWP). Carbon dioxide removal (CDR) technologies are possible with biochar production and use, and they can reduce the GWP[94-96]. The GWP can also be interpreted as an indicator of heat absorbed over a given time period due to emissions of a gas, compared with the emissions of 1 ton of carbon dioxide. The amount of carbon dioxide emitted is the reference to a GWP of 1, irrespective of time, but it is usually 100 years[97,98]. Carbon equivalents are used to estimate how much carbon dioxide would be produced by a mixture of emissions to have the same GWP and measured over 100 years[98]. Currently, cities consume 67%-76% of the global energy and contribute to 71%-76% of global carbon dioxide emissions[99]. These calculations highlight the reasons that the urban carbon footprint effect is so important to the GWP. Biochar produced from waste wood generated in urban environments is a rapid method for reducing the climate footprint of urban environments, but additional data is needed for each urban area to understand the biochar sink as related to other GHG emissions.

The importance of carbon sequestration, in general, is related to how urban vegetation carbon stocks can be managed to increase the rate of carbon assimilation and decrease the loss of carbon. In urban environments, this can be achieved through vegetation management plans that increase tree planting and that include tree care programs to decrease tree mortality, manage invasive insects and diseases, develop conditions to promote old-growth trees, and produce biochar from low- and no-value woody residues and other biomass products while also generating heat and energy. These steps will allow cities to increase carbon removals and achieve carbon neutral or negative energy for sustainable environments in the near future. In addition, although urban soils will benefit from the application of biochar, there are other markets where biochar could be used, such as in cement or asphalt[100].

This is also highlighted by the results of several life cycle analyses performed to elucidate the benefits of using biochar in urban environments. Roberts *et al*. (2010) estimated the energy production, climate change impacts, and economics of biochar systems with corn stover, yard waste, and switchgrass energy crops feedstocks[101]. Their results indicated that switchgrass has the greatest net energy of the system, and that GHG emissions for corn stover and yard waste are negative with -864 and -885 kg CO_2 equivalent (CO_2e) emissions reductions per ton of dry feedstock, respectively. The CO_2 reductions are estimated to be 62%-66% by increasing C sequestration through the creation of biochar. They concluded that biomass sources from waste management (yard waste) have the highest potential for economic profitability with +\$69 t^{-1} dry feedstock when CO_2e emission reductions are valued at \$80 t^{-1} CO_2e. They also noted that biochar may currently deliver climate change mitigation benefits and be financially viable as a distributed system using waste biomass. Similar conclusions were achieved by Homagain *et al*. (2015) when assessing the life cycle of biochar-based bioenergy production system with biochar land application conducted within a defined system boundary in Northwestern Ontario, Canada[102]. In Canada, land application of biochar had the most promising positive environmental impacts compared with conventional coal-based power generation system, when biomass availability is high. In another study, Azzi *et al.* (2019) studied the potential climate benefits of large-scale biochar production, connected to Stockholm's district heating system, and biochar use in dairy farming[103]. Their findings indicated that the effects of cascading biochar use in animal husbandry are uncertain but could provide 10%-20% more mitigation than direct biochar soil incorporation. In a decarbonized energy system, at the scale of the Uppsala, Sweden district, LCA results indicate that when comparing biochar products against reference products (e.g., tree, green roof, landscaping soil, charcrete, and biofilm) and oxidative use of biochar for steel production, all biochar products showed better climate performance than the reference products, and most applications outperformed biomass use for decarbonizing steel production. The climate benefits of using biochar ranged from - 1.4 to - 0.11-ton CO_2-eq ton^{-1} biochar in a decarbonized energy system[82].

CONCLUSIONS

There are many opportunities for enhancing the utilization of woody biomass from urban tree waste to increase biochar, bioenergy, compost, lumber, or chip production and subsequently reduce the national global warming potential and eutrophication potential, especially when compared to disposing of this material in a landfill. Further, although urban soils are considered suboptimal for most tree species to survive and grow, amendment with biochar could increase tree and soil health and productivity. Integrating urban tree planting efforts with biochar produced from local biomass can also decrease tree maintenance costs and promote soil carbon gains. Green infrastructure contributes to a host of benefits that include not only human and animal health, but also carbon sequestration. Using woody biomass from urban and suburban settings for bioproducts also allows for a reduction in the risk of wildfire, improving soil properties to support the long-term growth of trees, and enhancing other ecosystem services.

Current data and technologies are available to determine the amounts of woody biomass available and allow for the projection of bioproduct volumes and markets. Small areas, such as parks or riversides, may not make a large impact on carbon sequestration at a local scale, but scaling to a city area further reduces the urban carbon footprint.

Accelerating waste biomass conversion will also require addressing a range of policies related to the scale of conversion. Since biochar is generally considered a stable carbon product and can be used as a soil amendment, it provides an alternative to landfilling woody biomass and enables the full utilization of dead biomass.

Further, considering the availability of urban vegetation in the USA, the current biomass assessments, the potential for biochar production alone (no heat or energy produced or captured), and the availability of biomass often destined for a landfill (12.15 million m tons[92]), biochar production could result in approximately 4.8 million m tons sequestered carbon, which is approximately 16.0 m tons CO_2 equivalent (low limit). The assessment by Nowak *et al.* estimates that 33 million dry m tons of biomass could be converted to biochar, assuming a 20% conversion factor will yield 6.6 million m tons of biochar that, when using the greenhouse gas equivalencies calculator[104], would result in 22 million m tons of CO_2 equivalent (high limit) per year, with the caveat that this estimation is based on the assumption that all the trees would be removed[87]. This represents a large potential contribution to the decrease in the GWP in the USA alone. Biochar contributes many other ecosystem benefits, but the primary urban benefits are rapid soil carbon storage and a reduction in woody wastes at landfills.

Implications

This paper provides a broad overview of the potential of woody biomass biochar application to urban environments, and it considers several potential implications for society, climate change, and the environment.

Policy

Civil society and government entities at all levels can work together to develop a strategy that considers current policies, policy gaps, and incentives needed to establish actions to decrease the impacts of climate change on cities, such as the use of biochar for CO_2 reduction or soil carbon sequestration and support policies to include cities in voluntary carbon markets and government initiatives.

State forest management plans of urban forests can be considered in urban planning as some major cities in the USA are already conducting. However, to be able to support climate change mitigation using vegetation in urban environments, the consideration of CO_2 removal technologies can be included in management plans. Biochar is a technology that is safe and ready for deployment. In addition, the multiple benefits offered by biochar in urban areas make it a sustainable endeavor when waste management, biochar, and energy production are included as part of vegetation management plans.

The enactment of policies aimed at promoting the adoption of biochar production for enhanced carbon sequestration in and around urban forests would be facilitated through several means. This includes increasing biochar production, fostering biochar-related practices in government activities, and encouraging the adoption of biochar to improve home gardens and agriculture or tree farms. These concerted efforts will ultimately result in a significant increase in carbon sequestration.

Research

It is clear from this review that there is still a need for further research to enhance our understanding of the advantages of biochar in urban soil management. Specifically, within urban environments, it is essential to evaluate biochar sustainability, production costs using a variety of urban feedstocks and methods, economic feasibility, and technical limitations. Moreover, there is a necessity to educate potential users to promote the increased use and acceptance of biochar. Additionally, it is imperative to conduct social and environmental impact assessments (e.g., characterization of the potential feedstocks to minimize harm to humans, wildlife, and soil health).

Another research area to explore is the need for additional life cycle analyses of biochar production in urban environments, which include different technologies (pyrolysis systems), costs of feedstock recollection, pyrolysis equipment investments, production rate, and co-products value, and climate change impacts will also promote greater adoption of biochar technologies for cities.

Urban biochar production and use is relatively new (< 20 years) and, therefore, one method to increase biochar activities is to plan long-term research goals and objectives through a network of cities. This network could leverage larger datasets to effectively examine ecological, hydrological, and soil-specific responses to the use of biochar and the carbon storage and sequestration benefits.

DECLARATIONS

Acknowledgments

We are grateful to the editor and the anonymous referees for their helpful comments and suggestions.
It was supported by the US Department of Agriculture Forest Service.

Author contributions

Conceptualization: Rodriguez Franco C, Page-Dumroese DS
Writing original draft preparation: Rodriguez Franco C, Page-Dumroese DS
Writing review and editing: Rodriguez Franco C, Page-Dumroese DS

Availability of data and materials

Not applicable.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Copyright

REFERENCES

1. United Nations Department of Economic and Social Affairs, Population Division. World population prospects 2022: summary of results. 2022. Available from: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf [Last accessed on 8 Sep 2023].
2. United Nations, Department of Economic and Social Affairs, Population Division. World urbanization prospects 2018: highlights. 2019. Available from: https://population.un.org/wup/Publications/Files/WUP2018-Highlights.pdf [Last accessed on 8 Sep 2023].
3. Sukko K. Urban development in the United States, 1690-1990. Working paper 7120. National bureau of economic research. p. 46. Available from: https://www.nber.org/system/files/working_papers/w7120/w7120.pdf [Last accessed on 8 Sep 2023].
4. OpenStax college. The growing pains of urbanization, 1870-1900 - urbanization and its challenges. Available from: https://pressbooks-dev.oer.hawaii.edu/ushistory/chapter/urbanization-and-its-challenges [Last accessed on 8 Sep 2023].
5. United Sates Census Bureau. 2020 urban areas FAQs. Available from: https://www2.census.gov/geo/pdfs/reference/ua/2020_Urban_Areas_FAQs.pdf [Last accessed on 8 Sep 2023].
6. World Bank based on information from the United Nations population division. World urbanization prospects: 2018 revision. Available from: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?end=2021&start=2021&type=shaded&view=map&year=2021 [Last accessed on 8 Sep 2023].
7. Public space urban forestry division. Somerville urban forest management plan. Mayor's office of strategic planning and community development city of somerville. 2021. p. 364. Available from: https://www.somervillema.gov/urbanforestry [Last accessed on 8 Sep 2023].
8. Cowie A, Woolf D, Gaunt J, et al. Biochar, carbon accounting and climate change. In: Lehmann J, Joseph S, editors. Biochar for environmental management. Science, technology and implementation. London: Routledge; 2015.
9. Athanassiadis A, Crawford RH, Bouillard P. Overcoming the "black box" approach of urban metabolism. In: Crawford RH, Stephan A, editors. Living and learning: research for a better built environment: 49 th international conference of the architectural science association, the architectural science association and the university of melbourne. 2015. pp. 547-56. Available from: https://rest.neptune-prod.its.unimelb.edu.au/server/api/core/bitstreams/6f8ad749-51bf-560f-9f3e-303db1122e69/content [Last accessed on 8 Sep 2023].
10. IPCC. Urban systems and other settlements. In: Shukla PR, Skea J, Slade R, et al., editors. Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge and New York: Cambridge University Press. 2022. Available from: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_08.pdf [Last accessed on 8 Sep 2023].
11. Li D, Ma J, Cheng T, van Genderen JL, Shao Z. Challenges and opportunities for the development of MEGACITIES. *Int J Digit Earth* 2019;12:1382-95. DOI
12. Singh R, Verma P, Kumar SV, Srivastava P, Kumar A. Urban ecology and climate change: challenges and mitigation strategies. In: Bhadouria R, Upadhyay S, Tripathi S, Singh P, Editors. Urban ecology and global climate change. New York: John Wiley & Sons. 2022. Available from: https://onlinelibrary.wiley.com/doi/epub/10.1002/9781119807216 [Last accessed on 8 Sep 2023].
13. IPCC. AR4 climate change 2007: physical science basis. Contribution of working group 1 to the fourth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press. NOAA. State of the climate. National Overview. 2007. Available from: https://www.ipcc.ch/report/ar4/wg1/ Last accessed on 12 Sep 2023].
14. IPCC. Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, et al, editors. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press. 2011. Available from: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf [Last accessed on 8 Sep 2023].
15. Office of Management and Budget. 2010 standards for delineating metropolitan and micropolitan statistical areas; notice. 2010. Available from: https://www.govinfo.gov/content/pkg/FR-2010-06-28/pdf/2010-15605.pdf [Last accessed on 8 Sep 2023].
16. Leyk S, Uhl HJ, Connor SD, et al. Two centuries of settlement and urban development in the United States. *Sci Adv* 2020;6:eaba2937. DOI PubMed PMC
17. United Sates Census Bureau. U.S. and world population clock. Available from: https://www.census.gov/popclock/ [Last accessed on 8 Sep 2023].
18. Smith A. 2021 U.S. billion-dollar weather and climate disasters in historical context. 2022. Available from: https://www.climate.gov/news-features/blogs/beyond-data/2021-us-billion-dollar-weather-and-climate-disasters-historical [Last accessed on 8 Sep 2023].
19. Liu Z, Zhan W, Bechtel B, et al. Surface warming in global cities is substantially more rapid than in rural background areas. *Commun Earth Environ* 2022;3:219. DOI
20. Verma P, Singh R, Singh P, Raghubanshi AS. Critical assessment and future dimensions for the urban ecological systems. In: Verma P, Singh P, Singh R, Raghubanshi AS, editors. Urban ecology. Amsterdam: Elsevier; 2020. pp. 479-97.
21. Bhadouria R, Upadhyay S, Tripathi S, Singh P. Urban ecology and global climate change. New York: John Wiley & Sons; 2022. p. 352. Available from: https://onlinelibrary.wiley.com/doi/book/10.1002/9781119807216 [Last accessed on 8 Sep 2023].
22. Chester A, abd Lawron J. Atlas of disaster. Rebuild by design. Institute for Public Knowledge, New York University, and iParametrics. 2022. p. 342. Available from: https://rebuildbydesign.org/wp-content/uploads/2023/04/ATLAS-OF-DISASTER-compressed.pdf [Last accessed on 12 Sep 2023].
23. Sujathamma C. Environmental issues of urban areas and wellness. *Int J Sci Dev Res* 2019;4. Available from: https://www.ijsdr.org/

papers/IJSDR1905103.pdf [Last accessed on 8 Sep 2023].

24. World Health Organization. Urban planning for resilience and health: key messages - summary report on protecting environments and health by building urban resilience. Copenhagen: WHO Regional Office for Europe; 2022. Available from: https://www.who.int/europe/publications/i/item/WHO-EURO-2022-5650-45415-64990 [Last accessed on 8 Sep 2023].
25. Gaston KJ, Ávila-Jiménez ML, Edmondson JL. Managing urban ecosystems for goods and services. *J Appl Ecol* 2013;50:830-40. DOI
26. Barboza PE, Cirach M, Khomenko S, et al. Green space and mortality in European cities: a health impact assessment study. *Lancet Planet Health* 2021;5:e718-30. DOI
27. Croeser T, Garrard GE, Visintin C, et al. Finding space for nature in cities: the considerable potential of redundant car parking. *NPJ Urban Sustain* 2022;2:27. DOI
28. Connop S, Vandergert P, Eisenberg B, et al. Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure. *Environ Sci Policy* 2016;62:99-111. DOI
29. Raymond CM, Frantzeskaki N, Kabisch N, et al. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ Sci Policy* 2017;77:15-24. DOI
30. Cadenasso ML, Pickett TAS, Grove JM. Integrative approaches to investigating human-natural systems: the Baltimore ecosystem study. *Nat Sci Soc* 2006;14:4-14. DOI
31. Nowak JD, Stein MS, Randler BP, et al. Sustaining America’s urban trees and forests: a forests on the edge report. p. 27 Available from: https://www.fs.usda.gov/openspace/fote/reports/nrs-62_sustaining_americas_urban.pdf [Last accessed on 8 Sep 2023].
32. Millennium Ecosystem Assessment. Ecosystems and human well-being: synthesis. Washington DC: Island Press. 2005. Available from: http://www.millenniumassessment.org/documents/document.356.aspx.pdf [Last accessed on 8 Sep 2023]
33. Nowak JD, Greenfield JE. Declining urban and community tree cover in the United States. *Urban For Urban Green* 2018;32:32-55. DOI
34. Coville CR, Kruegler J, Selbig RW, et al. Loss of street trees predicted to cause 6000 L/tree increase in leaf-on stormwater runoff for Great Lakes urban sewershed. *Urban For Urban Green* 2022;74:127649. DOI
35. Pataki DE, Alberti M, Cadenasso ML, et al. The benefits and limits of urban tree planting for environmental and human health. *Front Ecol Evol* 2021;9. DOI
36. Shen YS, Lung CS. Can green structure reduce the mortality of cardiovascular diseases? *Sci Total Environ* 2016;566-7:1159-67. DOI
37. Crouse DL, Pinault L, Balram A, et al. Urban greenness and mortality in Canada's largest cities: a national cohort study. *Lancet Planet Health* 2017;1:e289-97. DOI
38. Donovan HG, Prestemon PJ, Gatziolis D, Michael YL, Kaminski AR, Dadvand P. The association between tree planting and mortality: a natural experiment and cost-benefit analysis. *Environ Int* 2022;170:107609. DOI
39. Sinha P, Coville CR, Hirabayashi S, Lim B, Endreny TA, Nowak DJ. Variation in estimates of heat-related mortality reduction due to tree cover in U.S. cities. *J Environ Manage* 2022;301:113751. DOI
40. Wolf KL, Lam ST, McKeen JK, Samsudin R. Urban trees and human health: a scoping review. *Int J Environ Res Public Health* 2020;17:4371. Available from: https://www.mdpi.com/1660-4601/17/12/4371 [Last accessed on 8 Sep 2023].
41. Zhang L, Tan PY, Gan RYD, Samsudin R. Assessment of mediators in the associations between urban green spaces and self-reported health. *Landsc Urban Plan* 2022;226:104503. DOI
42. United Kingdom Government. Department for environment, food and rural affairs. Tree Health Resilience Strategy. 2018. p. 63. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/710719/tree-health-resilience-strategy.pdf [Last accessed on 8 Sep 2023].
43. Nowak DJ, Greenfield EJ. U. S. urban forest statistics, values and projections. *J For* 2018;116:164-77. DOI
44. Lehmann J, Joseph S. Biochar for environmental management: an introduction. In: Lehmann J, Joseph S, editors. Biochar for environmental management: science and technology. London: Earthscan; 2009. pp. 1-12. Available from: https://www.biochar-international.org/wp-content/uploads/2018/04/Biochar_book_Chapter_1.pdf [Last accessed on 8 Sep 2023].
45. Manyà JJ. Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. *Environ Sci Technol* 2012;46:7939-54. DOI PubMed
46. Fuchs M, Garcia-Perez M, Small P, Flora G. Campfire lessons - breaking down the combustion process to understand biochar production and characterization.. *Biochar J* 2014. Available from: https://www.biochar-journal.org/itjo/media/doc1420082881242.pdf [Last accessed on 8 Sep 2023].
47. Hornung A, Stenzel F, Grunwald J. Biochar - just a black matter is not enough. *Biomass Conv Bioref* 2021. Available from: https://link.springer.com/article/10.1007/s13399-021-01284-5#citeas [Last accessed on 8 Sep 2023].
48. Mesa AC, Spokas KA. Impacts of biochar (black carbon) additions on the sorption and efficacy of herbicides. In: Kortekamp A, editor. Herbicides and environment. 2011. pp. 315-40. Available from: https://www.intechopen.com/chapters/12591 [Last accessed on 8 Sep 2023].
49. Harry GH, Howe J, Bowyer J, Levins RA, Fernholz K.Biochar as an innovative wood product: a look at barriers to realization of its full potential. 2017. Available from: https://www.dovetailinc.org/portfoliodetail.php?id=5e2622ce74378 [Last accessed on 8 Sep 2023].
50. Rockwood DL, Ellis MF, Liu R, et al. Forest trees for biochar and carbon sequestration: production and benefits. In: Abdelhafez AA, Abbas MHH, editors. Applications of biochar for environmental safety. London: IntechOpen; 2020. Available from: https://www.intechopen.com/chapters/72115#:~:text=DOI%3A%2010.5772/intechopen.92377 [Last accessed on 8 Sep 2023].

51. Baltar R. Report on options for utilization of surplus biomass coming from the Usal Forest. In: Redwood forest foundation. 2018. p. 81. Available from: https://www.rffi.org/Library/RFFI_Equipment_Alternatives_Report%2012_14_18.pdf [Last accessed on 8 Sep 2023].

52. Amonette JE, Blanco-Canqui H, Hassebrook C, et al. Integrated biochar research: a roadmap. *J Soil Water Conserv* 2021;76:24A-9A. DOI

53. Bridgwater AV. Catalysis in thermal biomass conversion. *Gen Appl Catal A* 1994;116:5-47. DOI

54. Bindar Y, Budhi WY, Hernowo P, Wahyu S, Saquib S, Setiadi T. 1 - sustainable technologies for biochar production. In: Ngo HH, Guo W, Pandey A, Varjani S, Tsang DCW, editors. Current developments in biotechnology and bioengineering. Amsterdam: Elsevier; 2023. pp. 1-40. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780323918732000133 [Last accessed on 8 Sep 2023].

55. Yu Q, Wang Y, Van Le Q, et al. An overview on the conversion of forest biomass into bioenergy. *Front Energy Res* 2021;9:684234. DOI

56. Gustafsson M. Stockholm biochar project. US biochar initiative presentations. 2018. Available from: https://biochar-us.org/sites/default/files/presentations/2.3.1%20Stockholm%20Biochar%20Project%20Mattias%20Gustafsson%20-.pdf [Last accessed on 8 Sep 2023].

57. Hellmann J, Gustafsson M, Ek L. Biochar-urban forestry strategy for the city of Stockholm, Sweden. Urban sustainability directors network. 2022. p. 13. Available from: https://carbonneutralcities.org/wp-content/uploads/2023/02/Stockholm-Strategy.pdf Last accessed on 12 Sep 2023].

58. Kärkkäinen A, Iliescu O, Jalas M, Salo E. Biochar-urban forestry strategy: biochar feedstock options, benefits, and potential applications in the greater Helsinki area. Urban sustainability directors network. 2022. p. 27. Available from: https://www.usdn.org/uploads/cms/documents/biochar_boulder_co.zip Last accessed on 8 Sep 2023].

59. Cambium carbon. biochar-urban forestry strategy for the city of boulder, colorado. urban sustainability directors network. 2022. p. 13. Available from: https://static1.squarespace.com/static/5d1e51dd2a98da000183bc20/t/63190210b6062c7def5f43b5/1662583317768/%28Cambium+Carbon%29+Boulder+Strategy_FINAL.pdf [Last accessed on 8 Sep 2023].

60. Cambium carbon. Biochar-urban forestry strategy for the city of Minneapolis, Minnesota. Urban Sustainability Directors Network. 2022. 13p. Available from: https://static1.squarespace.com/static/5d1e51dd2a98da000183bc20/t/6319024b58da104024ba7f28/1662583372474/%28Cambium+Carbon%29+Minneapolis+Strategy_FINAL.pdf [Last accessed on 8 Sep 2023].

61. Jatav HS, Rajput VD, Minkina T, et al. Sustainable approach and safe use of biochar and its possible consequences. *Sustainability* 2021;13:10362. DOI

62. Wilson KJ. A carbon conservation corps to restore forests with biochar using flame cap kilns. In: 2021 ASABE annual international virtual meeting. American Society of Agricultural and Biological Engineers. 2021. Available from: https://elibrary.asabe.org/techpapers.asp?confid=virt2021 [Last accessed on 8 Sep 2023].

63. McAvoy D. Hazardous fuels reduction using flame cap biochar kilns. Fact sheet 037. 2019. Available from: https://extension.usu.edu/forestry/publications/utah-forest-facts/037-hazardous-fuels-reduction-using-flame-cap-biochar-kiln [Last accessed on 8 Sep 2023].

64. Center of Biochar and Green Agriculture. An introduction to biochar technology and products available in China. Nanjing: Nanjing Agricultural University; 2015. 15p. Available from: https://dokumen.tips/documents/an-introduction-to-biochar-technology-and-products-an-introduction-to-biochar.html?page=3 [Last accessed on 8 Sep 2023].

65. Zhang X, Luo Y, Müller K, et al. Research and application of biochar in China. In: Guo M, He Z, Uchimiya SM, editors, Agricultural and environmental applications of biochar: advances and barriers. 2016. DOI

66. National Oceanic and Atmospheric Administration (NOAA). NOAA carbon dioxide removal research: a white paper documenting a potential NOAA CDR science strategy as an element of NOAA's climate mitigation portfolio. Carbon dioxide removal task force. 2022. Available from: https://sciencecouncil.noaa.gov/Portals/0/Documents/Clean%20copy%20of%20Draft%20CDR%20Research%20Strategy.pdf?ver=2022-09-21-143831-560 [Last accessed on 8 Sep 2023].

67. Campbell RM, Anderson NM, Daugaard DE, Naughton HT. Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. *Appl Energy* 2018;230:330-43. DOI

68. U.S. Biochar initiative. Biochar slows climate change. 2023. Available from: https://biochar-us.org/biochar-slows-climate-change [Last accessed on 8 Sep 2023].

69. HP Schmidt, C Kammann, N Hagemann. Certification of the carbon sink potential of biochar. Version 1.0E of 1st June 2020. Arbaz, Switzerland: Ithaka Institute, 2020. Available from: https://www.european-biochar.org/media/doc/2/c_en_sink-value_5.pdf [Last accessed on 8 Sep 2023].

70. IPCC. Chapter 6: cities, settlements and key infrastructure. In: Pörtner HO, Roberts DC, Tignor M, et al., editors. Climate change 2022: Impacts, adaptation and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, UK/New York, NY: Cambridge University Press; 2022. pp. 907-1040. Available from: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter06.pdf [Last accessed on 8 Sep 2023].

71. Smith P. Soil carbon sequestration and biochar as negative emission technologies. *Glob Change Biol* 2016;22:1315-24. DOI PubMed

72. Mohanty SK, Valenca R, Berger AW, et al. Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment. *Sci Total Environ* 2018;625:1644-58. DOI

73. Alvem BM, Embrén B. Trees and stormwater management-the stockholm solution. 2014. Available from: https://sfbiochar.com/docs/urban/Trees_and_Stormwater_Management_The_Stockholm_Solution.pdf [Last accessed on 8 Sep 2023].

74. Embrén B. Planting urban trees with biochar. Available from: https://www.biochar-journal.org/en/ct/77 [Last accessed on 8 Sep 2023].
75. Nordregio. Stockholm biochar project. 2018. Available from: https://nordregio.org/sustainable_cities/stockholm-biochar-project/#:~:text=This%20project%20reduces%20carbon%20emissions,soil%20for%20thousands%20of%20years [Last accessed on 8 Sep 2023].
76. Azzi ES, Karltun E, Sundberg C. Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. *Biochar* 2022;4:18. DOI
77. Fransson AM, Sandell B, Malmberg J, Pettersson L, Bernhoff SO, Bromell LO. Biochar in urban applications in bio-Char II: production, characterization and applications. 2019. Available from: https://dc.engconfintl.org/biochar_ii/15 [Last accessed on 8 Sep 2023].
78. Center for Regenerative Solutions. About center for regenerative solutions. 2023. Available from: https://naturebasedclimate.solutions/about [Last accessed on 8 Sep 2023].
79. Draper K, Schmidt HP. Urban bioenergy-biochar: an opportunity assessment for municipalities. Urban Drawdown Initiative & Ithaka Institute. 31p. 2021. Available from: https://biochar-us.org/urban-bioenergy-biochar-opportunity-assessment-municipalities [Last accessed on 8 Sep 2023].
80. Carbon Neutral Cities Alliance. Urban forest biomass to biochar playbook CNCA biochar-urban forest strategy. Urban Sustainability Directors Network. 2022. 11p. Available from: https://carbonneutralcities.org/wp-content/uploads/2023/02/BiocharPlaybook.pdf [Last accessed on 8 Sep 2023].
81. Lee J, Ko Y, Mcpherson EG. The feasibility of remotely sensed data to estimate urban tree dimensions and biomass. *Urban For Urban Gree* 2016;16:208-20. DOI
82. Lan K, Zhang B, Yao Y. Circular utilization of urban tree waste contributes to the mitigation of climate change and eutrophication. *One Earth* 2022;5:944-57. DOI
83. City of Nebraska. Lincoln awarded $400,000 for biochar initiative. 2022. Available from: https://klin.com/2022/06/29/lincoln-awarded-400000-for-biochar-initiative/ [Last accessed on 8 Sep 2023].
84. Salo E, Koivunen M, Passi S, Jalas, M. Report on concept designs for carbon drawdown. Carbon lane project. 2019. 44p. Available from: https://www.aalto.fi/sites/g/files/flghsv161/files/2020-02/Report%20on%20concept%20designs%20for%20carbon%20drawdown.pdf [Last accessed on 8 Sep 2023].
85. Hansen M, Howd P, Sallenger A, Wright WC, Lillycrop J. Estimation of post-katrina debris volume: an example from coastal mississippi. In: Science and the storms: the USGS response to the hurricanes of 2005. 2005. 6p. Available from: https://pubs.usgs.gov/circ/1306/pdf/c1306_ch3_e.pdf [Last accessed on 8 Sep 2023].
86. Hudgins EJ, Koch FH, Ambrose MJ, Leung B. Hotspots of pest-induced US urban tree death, 2020-2050. *J Appl Ecol* 2022;59:1302-12. DOI
87. Nowak DJ, Greenfield EJ, Ash RM. Annual biomass loss and potential value of urban tree waste in the United States. *Urban For Urban Green* 2019;46:126469. DOI
88. Environmental Protection Agency. Planning for natural disaster debris. 2008. 94p. Available from: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1004PRS.PDF?Dockey=P1004PRS.PDF [Last accessed on 8 Sep 2023].
89. Groot H, Pepke E, Fernholz K, Henderson C, Howe J. Survey and analysis of the US biochar industry. dovetail partners. 2018. 26p. Available from: https://www.dovetailinc.org/upload/tmp/1579550188.pdf [Last accessed on 8 Sep 2023].
90. Macfarlane DW. Potential availability of urban wood biomass in Michigan: implications for energy production, carbon sequestration and sustainable forest management in the U.S.A. *Biomass Bioenergy* 2009;33:628-34. DOI
91. Amonette JE, Archuleta JG, Fuchs MR, et al. Biomass to biochar: maximizing the carbon value. report by center for sustaining agriculture and natural resources. Pullman, WA: Washington State University; 2021. Available from: https://csanr.wsu.edu/biomass2biochar/ [Last accessed on 8 Sep 2023].
92. Environmental Protection Agency. Facts and figures about materials, waste and recycling. wood: material-specific data. 2022. Available from: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/wood-material-specific-data [Last accessed on 8 Sep 2023].
93. Kurniawan TA, Othman MHD, Liang X, et al. Challenges and opportunities for biochar to promote circular economy and carbon neutrality. *J Environ Manage* 2023;332:117429. DOI
94. Poroma D, Cerda R, Somarriba E, Cifuentes M, Guerra L. Carbon footprint: what is it and how to measure it? 2012. Available from: https://repositorio.catie.ac.cr/bitstream/handle/11554/7804/620.pdf?sequence=2 [Last accessed on 8 Sep 2023].
95. Lombardi M, Laiola E, Tricase C, Rana R. Assessing the urban carbon footprint: an overview. *Environ Impact Assess Rev* 2017;66:43-52. DOI
96. Selin NE. Carbon footprint. In: Encyclopedia britannica. Available from: https://www.britannica.com/science/carbon-footprint [Last accessed on 8 Sep 2023].
97. Environmental Protection Agency. Understanding global warming potentials. 2023. Available from: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why [Last accessed on 8 Sep 2023].
98. Vallero AD. Chapter 8 - Air pollution biogeochemistry. In: Air pollution calculations: quantifying pollutant formation, transport, transformation, fate and risks. Amsterdam, The Netherlands: Elsevier; 2019. pp. 175-206. DOI
99. United Nations. World urbanization prospects: the 2018 revision (ST/ESA/SER.A/420). 2019. Available from: https://population.un.org/wup/publications/Files/WUP2018-Report.pdf [Last accessed on 8 Sep 2023]. DOI

100. Rondón-Quintana HA, Reyes-Lizcano FA, Chaves-Pabón SB, Bastidas-Martínez JG, Zafra-Mejía CA. Use of biochar in asphalts: review. *Sustainability* 2022;14:4745. DOI

101. Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environ Sci Technol* 2010;44:827-833. DOI PubMed

102. Homagain K, Shahi C, Luckai N, Sharma M. Life cycle environmental impact assessment of biochar-based bioenergy production and utilization in Northwestern Ontario. *Canada J For Res* 2015;26:799-809. DOI

103. Azzi ES, Karltun E, Sundberg C. Prospective life cycle assessment of large-scale biochar production and use for negative emissions in stockholm. *Environ Sci Technol* 2019;53:8466-76. DOI PubMed

104. Environmental Protection Agency. Greenhouse gas equivalencies calculator. 2023. Available from: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results [Last accessed on 8 Sep 2023].