Biochar Benefits Analysis

CNCA BIOCHAR-URBAN FOREST STRATEGY

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Introduction

This paper is part of a collaborative project across four cities – Boulder, Helsinki, Minneapolis, and Stockholm – aiming to understand the feasibility and impact potential for local production and application of biochar from wood waste in each respective municipality. This analysis is one of several resources prepared in coordination with Nature-Based Climate Solutions (NCS) and supported by the Carbon Neutral Cities Alliance.

Biochar is a carbon-rich solid resulting from the thermal decomposition of organic matter in a low- or no-oxygen environment. The application of biochar in soil can provide a number of environmental benefits, from carbon storage to soil remediation. The following paper highlights several biochar benefits of particular relevance to urban forestry and land management applications, and the potential impact they can provide to communities.

Carbon Benefit

Recognized by the UN Intergovernmental Panel on Climate Change (IPCC) in 2018 as a negative emissions technology, biochar's emergence as a natural climate solution is driven by the potential to reduce emissions resulting from the decomposition of organic biomass, instead pyrolyzing material into a highly stable form of carbon.

The IPCC estimates that biochar derived from pyrolysis of woody biomass contains an average 77% organic carbon.[1] However, carbon content and long-term stability is highly variable subject to an individual production process. Table 1 highlights the general effect of temperature on persistent carbon content over 100 years, a time horizon often utilized by carbon offsetting methodologies for calculating long-term impact.[2]

Table 1. IPCC Estimated Stability of Biochar in Relation to Pyrolysis Temperature[3]

Production temperature	Fraction of persistent C after 100 years
High (>600 °C)	89% (± 13%)
Medium (450-600 °C)	80% (± 11%)
Low (350-450 °C)	65% (± 15%)

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[1] IPCC. (2019). Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development.

[2] Puro.earth. (2022, January). Biochar Methodology (Version 2.4.1).

[3] EcoTopic, "Carbon Sinks in Urban Public Green Areas: Calculations of Potential Carbon Storage in the City of Stockholm." April 6, 2022. See also: IPCC, 2019

Because carbon permanence of biochar will fluctuate significantly based on specific feedstock mix and production technology, a lab analysis is required for precise quantification of an individual biochar's carbon sequestration potential. Furthermore, cradle-to-gate life cycle assessments – which consider only emissions resulting from biochar production up to point-of-sale – may overlook significant carbon impacts from transportation emissions. As a result, the net carbon impact of biochar use will be subject to contextual variables within a specific production and application system.

Estimating Carbon Impacts (adapted from EcoTopic, 2022)[4]

In order to estimate biochar's potential to mitigate greenhouse gas emissions, the following section provides a simplified calculation method based on hydrogen to organic carbon ratio (H/C_{org}). Table 2 is drawn from the International Biochar Initiative (IBI) estimation of biochar BC_{+100}, which represents the amount of biochar carbon expected to remain stable after 100 years, relative to H/C_{org}.[5] It should be noted that IBI's chosen value of stable carbon is conservatively selected to be estimated below the lower limit of a 95% confidence interval.

Table 2. Biochar Stability Based on Biochar H/C_{org} at 95% confidence (Budai, et. al, 2013).

	BC_{+100} (%)			
H/C_{org}	**Mean**	**Lower limit**	**Upper limit**	**Chosen value**
0.4	**80.5**	**72.6**	**88.2**	**70**
0.5	73.1	67.1	78.9	50
0.6	65.6	60.5	70.6	50
0.7	**58.2**	**52.5**	**63.8**	**50**

Based on the BC_{+100} index, a simple calculation of a biochar's carbon sequestration potential can be estimated using the following formula:

$$CO_2 \text{ sequestration (at 100 years)} = \% C * BC_{+100} * 3.67$$

The present carbon content of the biochar (% C) is multiplied by BC_{+100} to reflect how much carbon will be present in the biochar after 100 years. Because a single atom of carbon binds with two heavier oxygen atoms to create a molecule of CO_2, the resulting carbon dioxide weighs 3.67 times the amount of its carbon content. As a result, to calculate CO_2 sequestered by biochar after 100 years, a multiple of 3.67 must be used.

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[4] EcoTopic, "Carbon Sinks in Urban Public Green Areas: Calculations of Potential Carbon Storage in the City of Stockholm." April 4, 2022

[5] Budai, A. et. al (2013). Biochar Carbon Stability Test Method: An Assessment of Methods to Determine Biochar Carbon Stability. International Biochar Initiative.

For example, one ton of biochar with 85% carbon content and an H/C_{org} ratio of 0.4 would be calculated as follows: 85% C * 70% * 3.67 tons of carbon dioxide equivalents = 2.18 tons CO_2 equivalent remaining after 100 years. This formula is offered as a baseline estimate for carbon impact calculation, until a more complete life-cycle assessment can be performed and certified.

Municipal Case Studies: Biochar Application Potential

The following section highlights a selection of promising application pathways and associated scale of bichar use within the project's four partner cities. Detailed city-specific analyses were conducted for each city, with excerpts provided here.

Stockholm (from EcoTopic, 2022)

A summary of common uses for wood-based biochar in Stockholm, Sweden, is provided in Table 3. The potential carbon sink in urban public green areas was calculated based on the formula presented in "Estimate Carbon Impacts," above. The calculations are also based on estimated feedstock availability[6] and the characteristics of biochar commonly used in Stockholm today, which usually contains 50-70% carbon and has a H/C_{org} of 0.2. The result is a factor of 2 tons of CO_2-eqv. that will remain after 100 years from biochar with a carbon content of 70%.

Table 3. Biochar Application Potential in the City of Stockholm

Application area	Use estimates	Biochar potential	Potential carbon sink
Green roofs	Per application: 30 vol% biochar in green roof substrate;. ≥80-100 mm substrate thickness Green roof area potential: 1-5 m^2 per capita	**Total**: 30-150,000m^3 (~6,000-30,000 tons)	**Total**: 12,000-60,000 tons CO_2e
Tree planting /urban forests, in vegetation	Per application: 5 vol% biochar * top 10 cm – or air-lance injection, approx. 40 L/tree. 1,000,000 trees in city limits; 10% of eligible	**Total**: 400m^3 (~ 80 tons)	**Total**: 160 tons CO_2e

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[6] EcoTopic, "Urban Feedstock Availability and Biochar Use Potential: A market Analysis of Stockholm and Sweden." April 6, 2022.

Application area	Use estimates	Biochar potential	Potential carbon sink
areas	for soil improvement (10,000 trees total)		
Tree plantings in structural soil	Per application: 7-20 vol% biochar. 15m^3 soil /tree ≈ 2 m^3 biochar/tree Yearly implementation: approx. 700 trees/year	Yearly: 1,400m^3 (~280 tons)	Yearly: 560 tons CO_2e
Urban plant beds, perennials	Per application: 12.5 vol% biochar Yearly implementation: 2-5 ha; 40 cm depth	Yearly: 1,000–2,500m^3 (~200– 500 tons)	Yearly: 400-1,000 tons CO_2e
Green areas (parks)	Per application: 5 vol% biochar in top 10cm soil Yearly implementation: 5 ha of park rebuilt/year	Yearly: 250 m^3 (~ 50 tons)	Yearly: 100 tons CO_2e
Peat substitute (e.g. potting soil)	Per application: 10-33 vol% biochar Yearly implementation: approx. 700 “city pots”; 750-1,000 m^3 peat-based soil	Yearly: 75-330 m^3 (~15- 66 tons)	Yearly: 30-132 tons CO_2e
Concrete (tree pit foundation + floor slabs)	Per application: 15 M% of cement substituted with biochar ≈ 2.25 M% biochar in concrete Yearly implementation: 300 tree pit foundations and 40,000 m^2 of concrete floor slabs (streets)	Yearly: 3.6 tons + 825m^3 (~165 tons)	Yearly: 330 tons CO_2e
	Totals:	**6,080 tons biochar + 714 tons annual**	**12,160 tons CO_2e + 1,420 tons CO_2e annual**

Note: in this case study biochar was converted from cubic meters to tons at a rate of 0.2 tons per cubic meter of volume. Summary totals are based on conservative (minimum) estimates.

Helsinki (from Aalto University, 2022)[7]

Researchers from Aalto University and VTT Technical Research Centre of Finland projected the biochar use potential in the Greater Helsinki area (Table 4).Conservative estimates are derived from current application practices within the city, and assuming minimum additions of biochar. Maximum potential was calculated based on further anticipated use cases, and assume a maximum rate of biochar inclusion. Annual values were obtained by proposing a maintenance or renewal rate of biochar application.

Table 4. Biochar Application Potential in Greater Helsinki

Application Area	Use estimates	Biochar potential		Estimated Carbon Sink
		Minimum	Maximum	
Tree planting	1,000 trees/year (8m^3 - 25m^3 soil per tree, with 10% biochar inclusion)	800 m^3 per year (240 tons)	2,500 m^3 per year (750 tons)	480-1500 tons CO_2e
Roof gardens & green walls	90,000 m^2 of green roofs (increasing 10% each year) 100mm thick soil layer, biochar included as 30% volume	270 m^3 per year (81 tons)	9,000 m^3 per year (2,700 tons)	162-5400 tons CO_2e
Sport fields	2,000,000 m^2 of sport fields with 10-15% maintenance rate; 0.4m thick soil layer; 5% biochar by volume	4,000 m^3 per year (1,200 tons)	6,000m^3 per year (1,800 tons)	2,400-3,600 tons CO_2e
Soil fill /structural soil	200,000m^3 – 475,000m^3 park/ vegetated roadside / bioswale /gardens; 10% biochar by volume	20,000 m^3 per year (6,000 tons)	47,500m^3 per year (14,250 tons)	12,000-28,500 tons CO_2e
Meadows & agricultural land	4,200,000 m^2 under City of Helsinki Administration; 300mm topsoil layer; 5-10% biochar by volume; 10% annual maintenance rate	6,300m^3 per year (1,890 tons)	12,600m^3 per year (3,780 tons)	3,780-7,560 tons CO_2e
Stormwater filter	Stormwater retention basins, biofiltration systems, etc.; estimated 10 new basis per year; soil thickness 0.5m-1m; biochar 10% volume	85m^3 per year (26 tons)	1,170m^3 per year (35 tons)	52-70 tons CO_2e

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[7] Iliescu, O., Jalas, M, and Salo, E. "Biochar benefits and potential applications in Greater Helsinki." Aalto University, May 2022.

Total:	9,437 - 23,315 tons biochar	18,874-46,630 tons CO_2e

Biochar volumes were converted to metric tons based on a conversion of .3 tons per cubic meter[8] and sequestered carbon dioxide equivalent was again assumed to be 2x for each ton of biochar use.

It should be noted that biochar use within construction projects – as infill and structural soil – presents the single largest area of application potential among the studied use cases. For example, a possible use suggested by the International Biochar Initiative is in the substrate soil layer under buildings and roads[9]. For infrastructure and development projects requiring site excavation and removal of topsoil, reincorporation of biochar as soil is returned to the site may help improve engineering properties while providing a significant use of biochar in the urban environment. While there is significant opportunity for biochar use in applications ranging from road and railway embankments to landfill cover and bioengineered slopes, the geotechnical properties of soil in these structures requires careful design, and the long-term effect of biochar application has not been studied as thoroughly as its agricultural uses.[10] Additional application areas for biochar may include utilization in concrete mixes and insulation.

Minneapolis

Within the City of Minneapolis, pilot projects utilizing biochar in roadside green infrastructure have shown promise in managing road runoff in meridian zones by absorbing and removing contaminants as water filters into the ground. As a result, the city's Public Works department would likely be the largest end users of biochar produced in the region. Table 4 provides a summary of target end users for city-generated biochar, and the estimated scale of annual use per category.

Table 5. Biochar Application Potential in the City of Minneapolis

User	Application Area	Use estimates	Biochar potential	Estimated Carbon Sink
Public Works	Roadside management (filtration of runoff)	1000+ miles of roadway. If 5% are rehabbed annually with 10% of projects including biochar as ⅙ of soil blend	80 tons	160-200 tons CO_2e annual

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[8] Lehmann, J., & Joseph, S. (2015). Biochar for Environmental Management - Science, Technology and Implementation.

[9] Major, J. (2010). Guidelines on Practical Aspects of Biochar Application to Field Soil in Various Soil Management Systems. International Biochar Initiative

[10] Hussaina et al. (2019). Influence of biochar on the soil water retention characteristics (SWRC): Potential application in geotechnical engineering structures. *Soil & Tillage Research*.

User	Application Area	Use estimates	Biochar potential	Estimated Carbon Sink
Urban Agriculture	Public giveaway (community gardens & resident use)	100 cubic yards	18 tons	36-45 tons CO_2e annual
Park Board & Urban Forestry	Tree planting	10,000 trees planted annually, 10-15% inclusion rate in soil/biochar/compost mix. Roughly ~2lbs biochar per tree	9 tons	18-23 tons CO_2e annual
Park Board & Urban Forestry	Green space / park land management	200 cubic yards	36 tons	72-90 tons CO_2e annual
		Totals:	**143 tons biochar**	**286 - 358 tons CO_2e annual**

Given that sequestration per ton of biochar typically ranges from 2-2.5 tons CO_2, the total carbon impact of biochar application in the categories identified in Table 5 is estimated to be between 286-358 tons annually. It is estimated that the City of Minneapolis could generate as much as 1,120 tons of biochar annually from local wood waste; as a result, engaging additional large-scale users (including the statewide Minnesota Department of Transportation) could help significantly drive offtake of the city's biochar and help reach a total carbon impact potential of more than 2,000 tons CO_2 equivalent annually.

Boulder

Table 6 identifies several application avenues for biochar use in the City of Boulder. Because of the region's arid climate and water stress, landscape application within the city's parks and green turf areas may present a particularly promising opportunity for utilization of biochar as a strategy to reduce water needs while increasing carbon storage on natural landscapes.

Table 6. Biochar Application Potential in the City of Boulder

User	Application Area	Use estimates	Biochar potential	Estimated Carbon Sink
Urban Forestry	Public tree planting	600-1,000 trees planted annually by the City of Boulder. Assumes 10-15% inclusion	1 ton	2-2.5 tons CO_2e annual

User	Application Area	Use estimates	Biochar potential	Estimated Carbon Sink
		rate in soil/biochar/compost mix, roughly ~2lbs biochar per tree.		
Urban Forestry	Community tree Planting	2,000 trees planted annually by community members. Assumes 10-15% inclusion rate in soil/biochar/compost mix, roughly ~2lbs biochar per tree.	2 tons	4 – 5 tons CO_2e annual
Parks & Recreation	Parks & turf management	1,918 acres of property maintained by Parks and Recreation. Estimate assumes biochar is applied at a rate of 0.41 lbs per square foot at 4in depth to between 1% - 5% total acreage	155 – 776 tons	311 – 1940 tons CO_2e annual
Urban Agriculture	Public giveaway (community gardens/ resident use)	100 cubic yards	18 tons	36 – 45 tons CO_2e annual
Public Works	Roadside management (filtration of runoff)	300 miles of city-managed roadway. Assumes 5% annual maintenance & 10% of projects including biochar as ⅙ of soil blend	24 tons	48–60 tons CO_2e annual
		Totals:	**200 - 821 tons biochar**	**400 - 2,053 tons CO_2e annual**

Assuming once again that sequestration per ton of biochar typically ranges from 2-2.5 tons CO_2, the total carbon sequestration potential of biochar use as outlined above ranges from 400 to 2,053 tons of carbon dioxide equivalent annually. This wide range stems predominantly from the significant range of potential use in turf applications. Given that urban forest biomass from tree maintenance activities within Boulder could provide enough feedstock to produce 1,356 tons of biochar annually, biochar application across these four identified use cases could be prioritized and scaled according to production volumes and non-carbon impact potential.

Plant Growth & Health[11]

Biochar & Tree Growth

One potential benefit of biochar application is the increased vitality and resilience of trees grown in a biochar-containing soil medium. A meta-analysis of published work on forest restoration and biochar applications found an average 41% increase in tree biomass from biochar additions.[12] While impacts may vary significantly based on environment, tree species, and growth context (eg. nursery propagation vs. forest plantings), biochar additions up to 20% of soil volume have shown consistent efficacy. Additions of biochar can help increase the pH of acidic soils and help stimulate tree growth and biomass yield[13]. Some adverse results may occur at inclusion rates greater than 20%, due to heightened levels of soil pH.

A 2014 study analyzed tree growth of two species – sugar maple (Acer saccharum) and Honey locust (Gleditsia triacanthos) – in three typical urban soils: sand, silt and compacted clay. Biochar was included as a top-dressing to soil surfaces at a rate of of 25 Mg per hectare per year (~.51 lbs per square foot). Across species and soil types, samples treated with a pine-based biochar saw a 44% increase in tree biomass, compared to control samples.[14] Additionally, research has shown that biochar can be a source of natural disease resistance. Biochar additions in potting mixes aided resistance to stem cankers caused by water mold in red oak and red maple.[15]

Use in Contaminated Soils

There have been a great number of studies (in the field, container growing and soil column experiments) looking at the effects of biochar on saline soils. There are two effects of saline soils on plant growth: osmotic stress, which inhibits plants from taking up water and ionic stress, whereby toxic ions such as sodium accumulate to excess in the plant and cause leaf chlorosis and eventually necrosis and reduced photosynthesis.[16] In saline and sodic soils with weak soil structure and low water availability, biochar can

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[11] Research contributed by James MacPhail of Sequest Ltd.

[12] Thomas, S.C. and Gale, N. 2015. New Forests 46 931-946 "Biochar and forest restoration: a review and meta-analysis of tree growth responses"

[13] Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P.C., et al., 2017. Potential role of biochars in decreasing soil acidification - a critical review. Sci. Total Environ. 581–582, 601–611.

[14] Scharenbroch, B. C., Meza, E. N., Catania, M., & Fite, K. (2014). Biochar and Biosolids Increase Tree Growth and Improve Soil Quality for Urban Landscapes. Journal of Environmental Quality, 42(5), 1372–1385.

[15] Zwart, D.C. and Kim, S-H. 2012. Hort Science 47 1736-40 "Biochar Amendment Increases Resistance to Stem Lesions Caused by Phytophthora spp. in Tree Seedlings"

[16] Akhtar, S. S., Andersen, M. N., & Liu, F. (2015). Biochar Mitigates Salinity Stress in Potato. Journal of Agronomy and Crop Science, 201(5), 368–378.

help reduce sodium absorption ratio, improving land quality for agriculture and vegetative growth.[17] In one 2015 study, soil treated with wood biochar saw an 80% reduction in exchangeable sodium, while saturated hydraulic conductivity and soil stability increased significantly.[18]

Contaminants including lead (Pb) have seen significant reductions with biochar addition to soil. A trial of maize grown in sandy loam soil containing Pb at rates of 4,600 mg/kg showed significant reductions (38 times less water-soluble Pb and 7 times less Pb concentration) when treated with a 5% amendment of oak wood-derived biochar and irrigated with saline water.[19] Additionally, increased soil conductivity from biochar in saline environments has shown 40-50% increases in uptake of Cadmium from soil with a 5% biochar addition, vs control samples.[20]

Because urban trees suffer from heavy metal and salt runoff in proximity to roadways, biochar's potential to absorb contaminants during infiltration holds particular promise for inclusion in street tree plantings and roadside green infrastructure projects. One study of urban runoff water filtration systems saw maximum absorption of both salt (sodium) and heavy metals (copper, zinc, lead and cadmium) when applied to a leaching column containing a mix of biochar and compost.[21]

Water Conservation

A final driver of biochar application may be the potential to increase water holding capacity and reduce irrigation demands in drought-prone environments. Numerous studies have shown that biochar can increase water-holding capacity and reduce soil compaction. As a result, significant yield increases have been found where medium and coarse textured soils have seen biochar added, likely to be due to improved water holding capacity.

In one study, biochar derived from maize cobs via slow pyrolysis was added to soils growing corn and soybeans. Results showed that for every 1% addition of biochar, available water and soil aggregate stability increased by 3%, while soil bulk density reduced by 3-5%.[22] These impacts could make a significant impact on agricultural viability and soil ecosystem health in regions with low or erratic rainfall.

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[17] Drake, J.A. et al.2016. Does biochar improve establishment of tree seedlings in saline sodic soils? Land Degradation and Development 27 52-59.

[18] Chaganti, V.N. et al. 2015. Leaching and reclamation of a biochar and compost amended saline–sodic soil with moderate SAR reclaimed water. Agric. Water Management 158 255-265

[19] Almaroai, Y. A., Usman, A. R. A., Ahmad, M., Moon, D. H., Cho, J. S., Joo, Y. K., Jeon, C., Lee, S. S., & Ok, Y. S. (2013). Effects of biochar, cow bone, and eggshell on Pb availability to maize in contaminated soil irrigated with saline water. Environmental Earth Sciences, 71(3), 1289–1296.

[20] Abbas, T. 2017. Effect of biochar on alleviation of cadmium toxicity in wheat (Triticum aestivum L.) grown on Cd-contaminated saline soil. Env. Science Pollution Res 2017 1-13

[21] Seguin, R. et al. 2018 Water Air Soil Pollution 229:84 1-15 "Remediating Montreal's Tree Pit Soil Applying an Ash Tree-Derived Biochar"

[22] Obia, A. et al. 2016. Soil and Tillage Research 155 35-44. "In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils."

Finally, a model developed by researchers from Rice University predicted that biochar application in soil could reduce need for irrigated water use by 37% in one studied site in Nebraska.[23] Given increasing water scarcity and associated cost considerations, the water conservation impacts – rather than carbon impact potential or soil health considerations – may be a the most critical driver in increasing municipal biochar use.

Conclusion

While carbon capture and storage is often a primary driver of biochar exploration, developing the use cases for local application will play an important role in catalyzing infrastructure investments and sustaining ongoing production. This paper aims to highlight a variety of benefits that have been identified from research into biochar's impact on plant growth and soil health, which may encourage local use in forestry and land management activities.

Upon comparing 4 case studies for city-scale biochar use (and associated carbon sequestration), it should be noted that total application potential in Helsinki is estimated significantly higher than in the 3 peer cities examined in this analysis. Because Helsinki has been home to much of the industry's early research and development, the scale of ambition and the variety of established pathways for local incorporation of biochar is more robust than in cities just beginning to develop biochar processing infrastructure and pilots.

While these summaries provide a high-level opportunity analysis for end use, the availability of production infrastructure and government support will play a significant role in the ultimate implementation of biochar application programs. That said, because biochar's climate and ecosystem impacts vary based on factors including feedstock, production process, and application context, it is recommended that pilot applications be performed and analyzed to validate local effects prior to large-scale production and use.

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[23] J.E. Kroeger, G Pourhashem, K.B Medlock, C.A Masiello. Water Cost Savings from Soil Biochar Amendment: A Spatial Analysis. GCB Bioenergy, 2020.