MAXIMIZING THE POTENTIAL OF BIOCHAR PRODUCTION FROM LOW-VALUE FOREST BIOMASS IN MICHIGAN: ASSESSING ECONOMIC AND ENVIRONMENTAL IMPACTS

By

Nafisa Nowshin Ahmed

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Forestry – Master of Science

2023

ABSTRACT

Accumulation of non-merchantable wood and low-value forest biomass risks forest health through pest infestation and diseases. Biochar has been proposed to mitigate the economic and environmental challenges involved with collecting, transporting, and handling unutilized forest biomass. Biochar is a carbon-rich product, produced through the thermal decomposition of biomass in the absence of oxygen. Since Michigan currently does not have any commercial biochar production facilities, there is a gap in information regarding the biochar market (potential supply and demand of biochar) and its potential use as a soil amendment in agriculture. We investigated if biochar production can be done from forest biomass and utilized for soil amendment when procurement is done through stationary and portable pyrolytic units. The first part of the study assessed the economic feasibility of biochar production in Michigan by optimizing transportation costs involved in determining the potential biochar demand and supply when 10 tons/acre of biochar is applied to cropland over a 30-year rotation. The study's second phase conducted a cradle-to-grave life cycle assessment (LCA) to quantify the environmental impacts of biochar production based on different production technologies. For baseline (delivered wood price of $23.25/green ton biomass or $25.54/green tonne biomass), to fulfill the potential biochar demand in the upper peninsula (UP), 132 portable units are required while it was only one stationary unit. For lower peninsula (LP), a higher number of units are required for both these approaches due to having more cropland in the land cover; the figures were 2 and 596 for stationary and portable units, respectively. Portable units can procure more biomass at the same optimized transportation cost but are only able to fulfill 57% of the potential biochar demand while stationary units can produce a surplus of 15%. Stationary units had the potential to reduce GWP by 14.78 tonne CO_2e/per state of Michigan while portable units can reduce GWP by 14.37 tonne CO_2e/per state of Michigan for portable units. The amount of carbon sequestered due to applying biochar as a soil amendment is 2.445 tonne CO_2e/ tonne biochar produced for both these systems, assuming that 86% of the carbon in biochar will remain in the soil. This research has bridged the knowledge gap regarding biochar production and utilization from economic and environmental feasibility perspectives, leading toward building a circular economy in Michigan.

ACKNOWLEDGEMENTS

I extend my heartfelt gratitude to my thesis advisor, Dr. Raju Pokharel, and committee members, Dr. Christopher Saffron and Dr. Jessica Miesel for their exceptional mentorship and invaluable insights. Their guidance, patience, and encouragement have been instrumental in shaping this research and refining my academic skills.

I am forever grateful to The Almighty for giving me the most incredible opportunity to pursue this degree at a pioneer land grant university. I am indebted to my partner and husband, Mohaimin Al Aoun, for his unwavering love and patience with me throughout this journey. I would not have been able to do this without the continuous support and strength from my brother, Nafeez, sister, Nuraysha, and mother, Humaira. I also want to thank my friends and colleagues, Naresh Khanal, Dr. Shivan G.C., Ichchha Thapa, Tara Allohverdi, Elliot Shanon, and Grayson White, for the camaraderie, helpful discussions, and relentless support. I would also like to mention my mental health counselor from MSU CAPS, Zhenshan Zhong, for his consistent support over the past two years, helping me overcome personal, academic, and emotional challenges. The presence of all these wonderful people has made this academic pursuit more enjoyable and fulfilling.

I would like to acknowledge the financial support Project GREEEN at Michigan State University provided that made this research possible. Their belief in the significance of this work has been instrumental in driving its successful completion. I am deeply thankful to everyone at the Department of Forestry, especially Katie James and Renee Brittain, The Great Lakes Biochar Network, the Office of International Students & Scholars, the College of Agriculture & Natural Resources, and The Graduate School for helping me navigate this journey as an international student and ensuring financial support through various fellowships.

In conclusion, I acknowledge all those who have played a part, big or small, in the completion of this thesis. Their support, encouragement, and contributions have been crucial in making this academic endeavor a reality.

TABLE OF CONTENTS

CHAPTER 1 : INTRODUCTION

Michigan is 55% forested (20.1 million acres) where the economic output from the forest products industry was $13.4 billion in 2019 (USFS, 2020). The forest wood products industry contributes to 4% of the manufacturing gross domestic product GDP and among the top 10 employers in 45 out of 50 states in the United States (US) (USFS, 2022). However, after harvesting operations are conducted, non-merchantable forest biomass and logging residues are left behind on the forest floors. Due to global warming, the biomass left on the ground keeps getting drier, and depending on the ecosystem, geographic location, climate, and weather the biomass can become fuel for starting wildfires (citation needed). In the US, 7,273fires were reported with 62.63 acres burned per fire (National Interagency for Fire Center (NIFC), 2023). In Michigan, DNR management responded to 274 fires in 2021 (an increase from the previous years) and burned 2,379 acres (MI DNR, 2021). The unused and untreated forest biomass also increases the risk of pest infestation and diseases, affecting forest health negatively. Costs associated with collecting, transporting, and handling biomass are the biggest obstacle towards biomass utilization. To overcome this challenge, biochar production from unused biomass has been proposed as a solution that can utilize existing natural resources for soil amendment in agriculture and manufacture biochar in Michigan instead of importing it from other states.

Biochar is produced using thermal decomposition of organic materials (known as pyrolysis) in an oxygen-deprived environment (Allohverdi et al., 2021). The type of feedstock used in biochar production determines the quality of biochar and the carbon content (Ippolito et al., 2020). Biochar's physio-chemical properties help it increase soil organic matter and nutrient content along with sequestering high rates of carbon (Smith, 2016). This helps in improving soil quality, crop yields while reducing the use of fertilizer and water use in agriculture (Qambrani et al., 2017). Slow pyrolysis is considered to be the ideal technology to produce biochar where the conversion yields vary between 25% and 50% (35% is the most widely used yield) (El-Naggar et al., 2019). On the other hand, fast pyrolysis produced bio-oil as the primary product and biochar as a secondary product with lower biomass to biochar conversion yields (12%-15% (Mašek, 2016), and 10%-20% (Chung et al., 2012).

Transportation distances, feedstock type, location of the biochar production facilities determine the performance of both stationary and portable biochar production systems (Sahoo et al., 2019). The biggest challenges in biomass utilization are the high costs of procurement and transportation, especially when the forest residues are used as feedstock (Yazan et al., 2016). To encourage more biomass use, reducing transportation costs for procurement can be the most effective strategy (Becker et al., 2009). Hence, in this study, transportation cost has been optimized to assess the economic feasibility of potential biochar facilities in Michigan. Subsequently, a life-cycle assessment has been conducted to identify the global warming potential of each production technology at optimized transportation costs to account for the environmental impact on biomass to biochar production. Utilizing existing forest resources for biochar production will help in generating local income, create local jobs while encouraging the use of local feedstock for boosting regional economy (Pergola et al., 2022).

This thesis aims to bridge the gap in information about the economic and environmental feasibility of biochar production using forest biomass in Michigan. Chapter 2 examines existing literature on biochar, its applications, production technologies, and policies that impact implementation and commercialization. The literature review also assesses available information on state and regional biomass supply for biochar production to identify any existing market, supply, and demand that can affect biochar use as a soil amendment in agriculture. After identifying the knowledge gap about forest biomass utilization for biochar production in Michigan, the economic feasibility of such systems is studied in Chapter 3 followed by Chapter 4 where the environmental impacts are discussed. Chapter 3 discusses the impact on potential biomass availability from federal, state, and private forests for procurement along with the potential supply, demand, and minimum selling price of biochar in Michigan. Chapter 4 adds to the information obtained through the analysis conducted in Chapter 3 and evaluates the contribution of each production stage through the metric of global warming potential. Based on the findings of Chapter 3 and Chapter 4, the final chapter, Chapter 5, talks about the conclusion of this study along with identifying limitations within the research scope and recognizing the future scope of research in this area.

REFERENCES

Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A review on current status of biochar uses in agriculture. Molecules, 26(18), 5584

Becker, D. R., Larson, D., & Lowell, E. C. (2009). Financial considerations of policy options to enhance biomass utilization for reducing wildfire hazards. *Forest Policy and Economics*, *11*(8), 628-635.

Chung, W., Kim, D., & Anderson, N. (2012, September). Productivity and cost analysis of a mobile pyrolysis system deployed to convert mill residues into biochar. In *Proceedings of the 35th Annual Meeting of the Council on Forest Engineering: Engineering New Solutions for Energy Supply and Demand New Bern, NC. Morgantown, WV2012*.

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., ... & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, *337*, 536-554.

Fire Management Section (Forest Resources Division). (2021). *Michigan 2021 Wildland Fire Report*. Michigan Department of Natural Resources. Available online : https://www.michigan.gov/dnr/-/media/Project/Websites/dnr/Documents/FRD/fire/Wildland-fire-report.pdf?rev=0de6a8b7103345349e9416e9b12dbfca#:~:text=Fire%20season%20summary,fires%20originated%20on%20private%20property. Last accessed on 8th August 2023.

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, *2*, 421-438.

Mašek, O. (2016). Biochar in thermal and thermochemical biorefineries—production of biochar as a coproduct. In *Handbook of biofuels production* (pp. 655-671). Woodhead Publishing.

Poudel, J. (2022). *Forest Products Industries' Economic Contributions: Michigan, 2019*. Michigan Department of Natural Resources. Available online : https://www.michigan.gov/dnr/-/media/Project/Websites/dnr/Documents/FRD/industry/economics/MI-Forest-ProductsIndustry-Report_2019.pdf?rev=b96f1f91f5b944f886f69f2670e016b2#:~:text=Michigan%20forest%20products%20industries'%20total,%2413.4%20billion%20(Table%201). Last accessed on 7th August 2023.

State of Michigan. (2023).*Wildfires*. Michigan prepares. Available on https://www.michigan.gov/michiganprepares/be-informed/wildfire. Last accessed on 7th August 2023.

National Interagency Fire Center (NIFC). (2023). *April 2023 Wildfires Report*. National Centers for Environmental Information. Available on : https://www.ncei.noaa.gov/access/monitoring/monthly-report/fire/202304. Last accessed on 8th August 2023.

Pergola, M. T., Saulino, L., Castellaneta, M., Rita, A., Pecora, G., Cozzi, M., ... & Ripullone, F. (2022). Towards sustainable management of forest residues in the southern

Apennine Mediterranean mountain forests: a scenario-based approach. *Annals of Forest Science*, *79*(1), 1-13.

Qambrani, N. A., Rahman, M. M., Won, S., Shim, S., & Ra, C. (2017). Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. *Renewable and Sustainable Energy Reviews*, *79*, 255-273.

Sahoo, K., Bilek, E., Bergman, R., & Mani, S. (2019). Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. *Applied Energy*, *235*, 578-590.

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global change biology*, *22*(3), 1315-1324.

USDA. (2022). *Forest Products*. US Forest Service. Available online : https://www.fs.usda.gov/research/forestproducts#:~:text=According%20to%20the%20American%20Forest,sector%20employers%20in%2045%20states. Last accessed on 9th August 2023.

USDA Forest Service. (2020). *Forests of Michigan, 2019*. Resource Update FS-235. Madison, WI: U.S. Department of Agriculture, Forest Service. 2p.

Yazan, D. M., van Duren, I., Mes, M., Kersten, S., Clancy, J., & Zijm, H. (2016). Design of sustainable second-generation biomass supply chains. *Biomass and Bioenergy*, *94*, 173-186.

CHAPTER 2 : LITERATURE REVIEW

Biochar is a porous material which can adsorb and retain a huge amount of water, despite varying efficiencies in different types of soil textures (Jatav et al., 2017). It can improve water holding capacity in sandy soils compared to loamy and clay soils when used as a soil amendment for agriculture (Glaser et al., 2002). Wang & Liu (2021) studied the effects of using biochar on greenhouse gas emissions and agricultural yield for upland and paddy soils in China and found that biochar's use as a soil amendment mixed with N fertilizer improved the production yields of rice and wheat by 12% and 17%, respectively. A statistical meta-analysis found that the improvement in crop productivity due to biochar was up to 10% on average for different types of feedstocks where the impact on yield varied between -28% and 39% for different acidic, neutral pH, coarse, and medium textured soils (Jeffery et al., 2011). The study also identified a lack of data that exists concerning biochar's effects for different geographical and environmental conditions across the globe, indicating a need for. There need to be more robust studies analyzing how land use and its changes are affected by biochar implementation for varying feedstocks. The absence of robust field data makes it very challenging to predict long-term effects on soil tillage, cultivation, and soil management.

Biochar has the potential to offset CO_2 emissions worldwide (Woolf et al., 2010). The carbon content in biochar varies with the pyrolytic conditions (temperature, moisture content, feedstock, residence time), making it challenging to quantify the impacts in a standardized way (Kamali et al., 2022a). The H/C_{org} ratio in biochar is an indicator of how much carbon can remain in the soil after 100 years of application and is dependent on the type of feedstock used during pyrolysis; biochar having a H/C_{org} ratio of 0.4 has 80.5% C left after 100 years (Budai et al., 2013). Woody feedstocks have a lower H/C_{org} ratio at higher pyrolysis temperatures (Ronsse et al., 2013). Biochar can reduce irrigation and fertilizer costs because of its organic matter and water retention capacity in soils, especially because it does not need to be applied every year (Oni et al., 2019). However, to full comprehend the impacts of surface-applied biochar and organic carbon input to deep soil depths, more detailed studies are required (Lorenz & Lal, 2014). The existing literature on biochar's effects on different geographical and environmental conditions across the globe is not sufficient to standardize application rates and portions of biochar. There need to be more robust studies analyzing how land use and its changes are affected with biochar implementation for varying feedstocks. Not having enough field data makes it very challenging to predict long-term effects on soil tillage, cultivation, and soil management.

The logistics cost of transporting biomass to industrial facilities is the biggest challenge to overcome for large-scale commercial biochar production systems using slow pyrolysis (Wrobel-Tobiszewska et al., 2015). The limited regional supply of biomass and high cost of biochar production as hurdles to biochar commercialization where feedstock costs were one third of the total biochar production costs, where 50% of it is due to collection and transportation costs (Sessions et al., 2019). The most important strategy to reduce biomass costs is the transportation distance, implying that reduction in transportation costs for biomass procurement can be the solution to increased biomass utilization (Becker et al., 2009). Procurement costs can be determined by the location and travel distance, where paying higher prices for biomass feedstock can increase the engagement of more processing plants and hence reduce transportation costs (Rosburg et al., 2016). Transportation costs along with availability of biomass are primary factors in designing biomass supply chain and location of processing facilities; the cost of fuel in transporting biomass also plays an important role in biomass procurement for biochar production (Van Holsbeeck & Srivastava, 2020).

Studies have been conducted to understand the relationship between transportation distance and logistics for applying biochar closer to where it is produced (Peters et al., 2015; Rosas et al., 2015). Hence, the alternative option of portable biochar production systems has been sought as a solution. It is necessary to evaluate all the associated impacts of biochar and its impact on the environment by conducting a life cycle assessment and investing in research to standardize the characterization of biochar (Yaashikaa et al., 2020). An LCA is a methodology to evaluate the environmental impacts caused by manufacturing till the end-of-life use of a product ((Muralikrishna & Manickam, 2017). There are four stages involved under ISO 14040 guidelines for conducting an LCA: i. goal and scope definition ii. inventory analysis iii. impact assessment iv. interpretation. LCAs can help in policymaking, product development, and environmental decision-making from a system analysis perspective while also recognizing strategies to contribute to social and economic viability ((Hellweg & Milà i Canals, 2014). However, lack of availability of relevant data, time, resources, and finances affects the quality of results an LCA can provide with (Curran, 2006).

LCAs have been adopted to estimate the impact of using different types of feedstocks (forest residues, agricultural waste, animal manure) with varying temperatures for thermal decomposition (pyrolysis, combustion, gasification) for biochar production. Slow pyrolysis is commonly used to produced biochar and is conducted between 300°C-700°C, with a conversion yield of 35% (Brown et al., 2011a). Biochar can also be produced using fast pyrolysis, which is conducted between 500°C-1000 °C, producing 12% biochar and 75% bio-oil (the primary product) (Pagliuso, 2010). On the other hand, there are portable pyrolytic units that produce on site and have conversion yields between 13%-20% (Eggink et al., 2018; Puettmann et al., 2020a) and 4%-10% (Delaney & Miles, 2019). In this study, the stationary facilities resemble large commercial reactors with conversion yields of 35% while the portable facilities considered here account for the average conversion yield of existing portable pyrolytic units at approximately 18.6% (average of the figures obtained through literature review).

Biochar could offset 9% of Europe emissions per year (Glaser et al., 2009) and up to 4.5% of annual national carbon emission in China, sequestering approximately 920 $kgCO_2e$ per ton of crop residues used as feedstock (Yang et al., 2021). Other feedstock materials, such as corn stover, yard waste, and energy crops have also been studied to identify the impact on biochar quality (Roberts et al., 2010) but a comparison between stationary and portable units using biomass forest residues is new, especially for Michigan that does not have any biochar processing facilities yet. In this thesis, we are assessing the systems where biochar is produced as a primary product. Regionalization of biochar production using locally available feedstock can help in expanding the biochar-based circular economy (Shahid et al., 2022). Bioeconomy is the exploration and exploitation of bio-resources to create new bioproducts that can have an economic contribution to the economy (Oni et al., 2019). When biochar is produced in rural regions, it causes a development in small and medium-sized enterprises, where waste from one process can be utilized as the input for the other and contributing to building a circular economy.

This thesis aims to address the knowledge gap that exists between stationary and portable production technologies when forest biomass is used as feedstock to meet potential biochar demand in Michigan agriculture. The research objectives attempt to quantify the potential feedstock supply for biochar production and evaluate the potential biochar demand as a soil amendment based on the agricultural needs in Michigan. Stakeholders in forestry and agriculture, and policymakers will have access to more information about the environmental viability of such biochar systems, helping them evaluate if investing in biochar will be beneficial and sustainable for the state.

This study examines the economic and environmental impacts of optimizing transportation costs involved during biomass procurement and biochar application to evaluate its prospects in the state. The broader objectives of the study are as follows:

i. Identify potential locations and feedstock supply of forest biomass within an economically feasible procurement zone to establish biochar manufacturing facilities
ii. Quantify environmental impacts of producing biochar using a life-cycle assessment methodology for stationary and portable facilities in Michigan

To accomplish these objectives, we investigated the following research questions:

i. What are the potential locations for biochar production using forest biomass?
ii. What is the potential demand for biochar in Michigan?
iii. How much biomass feedstock is available?
iv. What is the price of locally produced biochar?
v. How much biochar can be produced using the different production technologies?
vi. What is the effect of conversion yields on global warming potential?
vii. What is the net global warming potential for stationary and portable processing facilities?
viii. What are the biggest contributors to global warming potential among all the production stages during biomass to biochar conversion?

REFERENCES

Becker, D. R., Larson, D., & Lowell, E. C. (2009). Financial considerations of policy options to enhance biomass utilization for reducing wildfire hazards. *Forest Policy and Economics*, *11*(8), 628-635.

Brown, T. R., Wright, M. M., & Brown, R. C. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining*, *5*(1), 54-68.

Budai, A., Zimmerman, A. R., Cowie, A. L., Webber, J. B. W., Singh, B. P., Glaser, B., ... & Joseph, S. (2013). Biochar Carbon Stability Test Method: An assessment of methods to determine biochar carbon stability. *International biochar initiative*, *20*.

Curran, M. A. (2006). EPA: Life cycle assessment: Principles and practice. *Scientific Applications International Corporation (SAIC)*.

Delaney, M., & Miles, T. (2019). Economics of mobile and stationary biochar production systems using juniper feedstocks in Oregon. *Corvallis, OR: USDA–ARS, Oregon State University*.

Eggink, A., Palmer, K., Severy, M., Carter, D., & Jacobson, A. (2018). Utilization of wet forest biomass as both the feedstock and electricity source for an integrated biochar production system. *Applied Engineering in Agriculture*, *34*(1), 125.

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. *Biology and fertility of soils*, *35*, 219-230.

Glaser, B., Parr, M., Braun, C., & Kopolo, G. (2009). Biochar is carbon negative. *Nature Geoscience*, *2*(1), 2-2.

Hellweg, S., & Milà i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, *344*(6188), 1109-1113.

Jatav, H. S., Jayant, H., Kumar, S., Kumar, V., Chattopadhya, A., Dhawal, S. K., & Singh, Y. V. (2017). Role of Biochar: In agriculture sector its implication and perspective. *Int J Chem Stud*, *5*, 14-18.

Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, ecosystems & environment*, *144*(1), 175-187.

Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T. M., & Dewil, R. (2022). Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chemical Engineering Journal*, *428*, 131189.

Lewis, H., & Demmers, M. (1996). Life cycle assessment and environmental management. *Australian Journal of Environmental Management*, *3*(2), 110-123.

Muralikrishna, I. V., & Manickam, V. (2017). Life cycle assessment. *Environmental management*, *11*(1), 57-75.

Oni, B. A., Oziegbe, O., & Olawole, O. O. (2019). Significance of biochar application to the environment and economy. *Annals of Agricultural Sciences*, *64*(2), 222-236.

Pagliuso, J. D. (2010). Biofuels for spark-ignition engines. In *Advanced direct injection combustion engine technologies and development* (pp. 229-259). Woodhead Publishing.

Peters, J. F., Iribarren, D., & Dufour, J. (2015). Biomass pyrolysis for biochar or energy applications? A life cycle assessment. *Environmental science & technology*, *49*(8), 5195-5202.

Puettmann, M., Sahoo, K., Wilson, K., & Oneil, E. (2020). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production*, *250*, 119564.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental science & technology*, *44*(2), 827-833.

Ronsse, F., Van Hecke, S., Dickinson, D., & Prins, W. (2013). Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *Gcb Bioenergy*, *5*(2), 104-115.

Rosas, J. G., Gómez, N., Cara, J., Ubalde, J., Sort, X., & Sánchez, M. E. (2015). Assessment of sustainable biochar production for carbon abatement from vineyard residues. *Journal of analytical and applied pyrolysis*, *113*, 239-247.

Rosburg, A., Miranowski, J., & Jacobs, K. (2016). Modeling biomass procurement tradeoffs within a cellulosic biofuel cost model. *Energy Economics*, *58*, 77-83.

Sessions, J., Smith, D., Trippe, K. M., Fried, J. S., Bailey, J. D., Petitmermet, J. H., ... & Campbell, J. D. (2019). Can biochar link forest restoration with commercial agriculture?. *Biomass and Bioenergy*, *123*, 175-185.

Shahid, M. K., Kashif, A., Choi, Y., Varjani, S., Taherzadeh, M. J., & Rout, P. R. (2022). Circular bioeconomy perspective of agro-waste-based biochar. In *Biomass, Biofuels, Biochemicals* (pp. 223-243). Elsevier.

Van Holsbeeck, S., & Srivastava, S. K. (2020). Feasibility of locating biomass-to-bioenergy conversion facilities using spatial information technologies: A case study on forest biomass in Queensland, Australia. *Biomass and Bioenergy*, *139*, 105620.

Wang, Z., & Liu, F. (2021). Environmental assessment tools. In *Industrial Ventilation Design Guidebook* (pp. 435-448). Academic Press.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature communications*, *1*(1), 56.

Wrobel-Tobiszewska, A., Boersma, M., Sargison, J., Adams, P., & Jarick, S. (2015). An economic analysis of biochar production using residues from Eucalypt plantations. *Biomass and Bioenergy*, *81*, 177-182.

Yaashikaa, P. R., Kumar, P. S., Varjani, S., & Saravanan, A. (2020). A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnology Reports*, *28*, e00570.

Yang, Q., Mašek, O., Zhao, L., Nan, H., Yu, S., Yin, J., ... & Cao, X. (2021). Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation. *Applied Energy*, *282*, 116275.

CHAPTER 3 : ASSESSING THE FEEDSTOCK AVAILABILITY OF FOREST BIOMASS FOR BIOCHAR PRODUCTION IN MICHIGAN AND IDENTIFYING POTENTIAL DEMAND, SUPPLY, AND COST OF BIOCHAR

Abstract

Accumulation of non-merchantable timber products, low-value wood, and logging residues risks forest health through wildfire, pest infestation, and diseases. Biochar (a carbon-rich bioproduct) has been proposed to mitigate the economic challenges involved with collecting, transporting, handling, and utilizing unused forest biomass. Transportation costs were optimized to determine the potential demand when 10 short tons (t) per acre of biochar is applied to cropland over a 30-year rotation. Forest ownership maps were overlaid with potential locations at different delivered wood prices for stationary and portable facilities and estimated potential forest biomass (net annual woody biomass increase) supply using the Forest Inventory Analysis (FIA) database. We evaluated the cropland acreage to determine the potential biochar demand as a soil amendment. There is a 71% potential surplus of biochar in the upper peninsula (UP) for stationary units at a biochar service area cost of $15.11/t whereas it was only 10% in the lower peninsula (LP). However, for portable units, there was a potential biochar deficit of 4% in UP and 50% in LP. Although portable facilities can procure a higher amount of biomass per unit cost, they produced less biochar due to lower conversion compared to stationary units. The minimum selling price of biochar (MSP) was $1,473/t on average for stationary units at *baseline* while it was higher at approximately $2,351/t for portable units. The MSPs were higher in the UP for both portable and stationary units. The study outcomes help bridge the knowledge gap on resource availability and utilization of forest resources while producing and land-applying biochar for climate change mitigation and carbon sequestration.

Keywords: *delivered wood price, forest biomass, low-value wood, portable units, procurement zones, stationary units*

Highlights

- Portable units can procure more biomass at the same transportation cost & delivered wood price.
- Private forests can supply 1.64 times more biomass on average through portable units.
- LP has around 2.5 times higher potential biochar demand than UP.
- The average biochar MSP is $1,473/t for stationary units and $2,351/t for portable units.

3.1 BACKGROUND

In the United States (US), the forest wood products industry is among the top 10 employers in 45 out of 50 states, accounting for 4% of manufacturing gross domestic product (GDP) and total products worth $300 billion annually (USFS, 2022). Michigan has 20.1 million acres of forested lands (55% of land cover) and is primarily focused on manufacturing commercial timber where the economic output from the forest products industry was $13.4 billion in 2019 (Poudel, 2022). The forest products industries employed over 91,000 people in 2017 with $8 billion in value-added products and $20.2 billion in economic output (Jolley et al., 2020). However, forest harvesting operations create byproducts via residual forest biomass, where 25%-45% of it is left behind after harvesting (Hakkila & Parikka, 2002; Smith et al., 2004). The residual forest biomass includes a mix of foliage bark, small-diameter trees, branches, and non-merchantable larger stems (Rudra & Jayathilake, 2022). The unused woody waste and logging residues increase the risk of wildfire and forest health issues through pest infestation and diseases.

Biochar has been proposed as a solution to mitigate the economic and environmental challenges associated with managing low-value forest biomass. Biochar is a product of the thermal decomposition of organic materials, a chemical process known as pyrolysis, which in the absence or near absence of oxygen.(Allohverdi et al., 2021). Biochar quality varies with the biomass type used as feedstock, directly impacting biochar's physicochemical properties, especially its carbon content (Ippolito et al., 2020). Overall, biochar technology has the potential to remove more than 1,000 gigatons of carbon dioxide globally (Amonette et al., 2021). For example, approximately 12% of the anthropogenic carbon emissions from land use change can be offset annually in the soil if slash-and-burn practices in forestry are replaced with slash and biochar practices (Lehmann, 2007). Interest in biochar as a soil amendment has been steadily increasing due to its potential for long-term soil carbon sequestration (Lehmann, 2007; Lehmann & Joseph, 2015).

Biochar's physical and chemical characteristics make it a great component to increase soil organic matter and nutrient content and sequester high carbon rates (Smith, 2016). Biochar as a soil amendment can enhance soil quality, and crop productivity while reducing fertilizer and water use (Qambrani et al., 2017). The use of forest biomass for biochar production for dryland agricultural applications improves water-holding capacity and crop yield (Sessions et al., 2019).

When mixed with chemical fertilizers and applied to agricultural lands, biochar increases crop yields between 45%-250% (Jha et al., 2010). The use of biochar for improving crop yields can help in fulfilling the anticipated global food demand; the world population is expected to increase to 10 billion by 2050 and not having enough agricultural productivity and security poses a risk to the land and water resources globally (Agegnehu et al., 2017). However, despite having merits for being used as a soil amendment, biochar's adoption in agriculture has been very slow due to financial barriers (Pourhashem et al., 2019).

Michigan currently does not have any commercial biochar processing facilities however there are commercial distributors who produce or import biochar from other states (such as Alabama) and process it for land applications (American Biochar Company, 2023). This indicates existing biochar demand in Michigan, but it is also an indicator that these companies prefer producing, transporting, and distributing biochar from other states than producing and distributing it within Michigan. The limited regional biomass supply and the high cost of biochar production are hurdles to biochar commercialization (Sessions et al., 2019). Biochar has not received attention like other bioproducts such as biofuel when policies regarding renewable energy transitions are implemented, primarily due to the latter being higher in energy and economic value (Pourhashem et al., 2019). However, biochar-blend requirements in fertilizers could improve biochar demand and utilization and allow farmers to mitigate unintended negative environmental impacts when conventional fertilizers are applied (Wu & Tanaka, 2005). The high cost of collection and transportation across a largely distributed area is the biggest hurdle to the utilization of biomass, especially forest residues (Yazan et al., 2016) and creates a barrier towards commercialization for farmers and farm income (Burton et al., 2008; Stroman & Kreuter, 2015). Having low bulk and energy density along with high moisture content also makes handling costs of procurement high (Sahoo et al., 2018). Transportation distances, feedstock type, and locations of biochar production systems (stationary and portable) strongly influence the performance of a biochar system (Sahoo et al., 2019). The most important strategy to reduce biomass costs is the transportation distance, implying that reduction in transportation costs for biomass procurement can support increased biomass utilization (Becker et al., 2009).

Feedstock costs have been estimated as one-third of the total biochar production costs, with 50% of it due to collection and transportation costs (Sessions et al., 2019). Transportation costs of raw materials are 60% of the overall project costs and having markets closer to harvest sites was the best solution to overcome the high transportation costs (Becker et al., 2009). However, it should be noted that having markets and harvest sites in close proximity is tough to achieve because of irregular local markets and quick saturation within one local region. Transportation cost and availability of biomass are primary factors in designing biomass supply chains and the location of processing facilities (Van Holsbeeck & Srivastava, 2020). In addition, the cost of fuel in transporting biomass also plays an important role in biomass procurement for biochar production; a 20% increase in energy costs caused a 7% increase in procurement costs (Rauch & Gronalt, 2011).

Pourhashem et al., (2019) analyzed different policy programs in the US that directly or indirectly support biochar production. There are 35 policy programs in total, which provide support either as a one-time grant or on a recurring basis. Among these, 15 are commercial incentive programs directed toward producers of biomass and bio-based products (such as biochar, and biofuel) through loan guarantees, grants, tax credits, and matching payments. For example, Biorefinery, Renewable Chemical and Biobased Product Manufacturing Assistance Program provides up to $250 million per project and covers up to 80% of the total eligible project costs as loan guarantees. There are 12 non-financial policy support programs that focus on tackling environmental challenges through carbon emission mitigation strategies, where biochar production could be a solution. These non-financial policy programs can play a vital role in creating biochar demand by including it in programs for forest conservation and fertilizing materials. In addition, there is $29.54 million allocated for research and development through the remaining eight programs. These programs support biochar production in the fields of agriculture, conservation of biomass, and bio-waste utilization, which offer support through a rigorous and competitive process.

Lack of a supportive legal policy framework and low demand for biochar are the main reasons for biochar market failures (Stefano Verde, 2021). Multiple certification schemes have been mobilized since 2016 to standardize biochar quality globally; some include the European Biochar Certificate in Europe, Biochar Quality Mandate in the UK, US Biochar Initiative (USBI), and International Biochar Initiative (IBI). There is a limited biochar market and demand today, so it is important to enable more stakeholder engagement in identifying the most suitable biochar for a particular kind of soil (Meyer et al., 2017). The knowledge gap in the scientific understanding of biochar in soils needs to be bridged, including socio-economic and time-scale factors in establishing a biochar market and increasing demand regionally (Verheijen et al., 2012). Although biochar's use as a soil amendment has been known to be great for carbon sequestration, more comprehensive studies need to be conducted on cross-sectoral policy frameworks to fully evaluate the impacts on the economy (Stefano Verde, 2021).

Furthermore, decentralized biochar production can help in creating employment opportunities, encourage better waste management along with causing an increase in resource proficiency in a circular economy (Yaashikaa et al., 2020). When biochar is produced in rural regions, it causes a development in small and medium-sized enterprises, where waste from one process can be utilized as the input for the other and contributes to building a circular economy. Regionalization of biochar production using locally available feedstock can help in expanding the biochar-based circular economy (Shahid et al., 2022). Lowering feedstock costs, achieving economies of scale and high carbon market prices will ensure large-scale utilization of non-merchantable, low-value forest biomass, as feedstock for biochar production (Elias et al., 2021). Biochar production from agricultural waste can create indirect and induced regional economic benefits; the production costs lied between \$448.78/t –\$1,846.96/t of biochar in California's Central Valley (Nematian et al., 2021). However, there is still missing information on when forest biomass is used for biochar production, especially for stationary and mobile units being compared in parallel.

Using existing natural resources (such as forest biomass), would not only help introduce a new forest product for agriculture in Michigan but also provide opportunities to create jobs, generate income, especially in rural and remote regions, and help promote the use of local feedstocks for local communities (Pergola et al., 2022). This study approach optimizes transportation costs for biomass procurement through stationary and Portable facilities within the geographical scope of Michigan. Previous studies have analyzed biochar production using either stationary facilities or made a comparison between different mobile units, but no direct comparison between stationary and mobile production units was made. This study's goal is to fill the knowledge gap on biomass procurement for different forest ownership types with varying delivered wood costs. The research objectives include quantifying the amount of biomass available for procurement through stationary and Portable units from federal, private, and state forests in Michigan. The study also investigates the potential supply of biochar by considering different conversion yields for production technologies and calculates the potential biochar demand using the cropland area for different optimized transportation costs. The research findings will help determine the minimum selling price of biochar (MSP) and help assess biochar's role in building a circular economy in Michigan.

3.2 MATERIALS AND METHODS

Data

The Michigan Department of Natural Resources (MI DNR) conducted a survey in 2019 to estimate the average delivered wood price at $23.25/green t of biomass which was used in this study to map procurement zones and service areas for biomass procurement. ESRI detailed street maps (ESRI, 2017) were used to conduct the road network analysis. Biomass availability was estimated using the Forest Inventory Analysis (FIA) from USDA Forest Service DataMart (USFS, 2021). Land coverage data were obtained from National Land Cover Database (USGS, 2019).

Selection of potential locations for biochar production in Michigan

Michigan currently operates eight bioenergy facilities that utilize wood waste, forest residues, and mill waste as feedstock, with a primary focus on power generation (Biomass Magazine, 2022). Among these facilities, one is located in Baraga County in UP, while two are situated in the southern LP regions (Kent and Genesee County). The remaining five facilities are found in the northern LP regions in Wexford, Alcona, Missaukee, Crawford, and between Alpena and Montmorency. Despite having several bioenergy facilities, Michigan currently lacks any biochar processing facilities. However, it does possess processing facilities that utilize biochar for various land applications, predominantly sourced from forest biomass in the southern United States (American Biochar Company, 2023). This indicates a significant demand for biochar and biochar-enriched products within Michigan. Considering this demand, two locations have been identified -one in the UP and the other in the LP for establishing biochar processing facilities. These locations were presented to the regional stakeholders, ensuring local support for the initiative.

Grayling City in Crawford County was carefully chosen for LP's biochar manufacturing facility based on several strategic factors. Firstly, Grayling's proximity to other industries in the area presented an opportunity for industry clustering, potentially fostering collaboration, and efficiency, help the local community more accepting of industrial scale power generation (Mittlefehldt et al., 2021). Secondly, the city's well-developed transportation infrastructure offered better logistical advantages for the facility's operations (Figure 3.1). Additionally, Grayling's location almost at the center of the northern LP was a key factor in the decision-making process. This central positioning allows the facility to procure forest biomass from all directions, optimizing the collection process (Figure 3.1). Moreover, the presence of Interstate 75 running through Grayling provides a direct route for the delivery of biochar to the southern LP, where most of the croplands in the state are located. This ensures a smooth and convenient distribution of the biochar and biochar-enriched products to their target markets. Coastal locations were avoided in the selection process, as they might impose limitations on collecting biomasses in different directions, potentially hindering efficient procurement. Similarly, locations with large population sizes, such as Detroit in the southern LP, were excluded to minimize disruptions in heavily populated urban areas with schools, hospitals, and offices. Overall, the primary motivation behind selecting Grayling was to establish a production facility in an area with the largest possible procurement region for forest biomass, thus ensuring a stable and abundant supply of raw materials. Additionally, the decision aimed to leverage the benefits of industry clustering and capitalize on the major road system passing through Grayling, enhancing the overall viability and success of the biochar manufacturing operation. Crawford County hosting Grayling has a civilian workforce of 49.1% (US Census Bureau, 2018) where 61% of the total land cover is forest.

Escanaba in Delta County was strategically chosen for UP's biochar manufacturing facility based on several key factors. Firstly, the presence of existing forest product industries in the area offered an opportunity for synergistic collaboration and potential resource sharing, enhancing overall operational efficiency. Secondly, Escanaba's transportation advantages played a crucial role in the decision. The city benefits from well-developed road networks and boasts a deep-water port, providing cost-effective and convenient options for transporting biochar products. This port can serve as a valuable asset for transporting biochar to southern Michigan. Another essential consideration was the abundant forested land in the UP (45% of Michigan’s forests are in UP (Pugh, 2018), making it an ideal location for sourcing forest biomass, the primary feedstock for biochar production. Additionally, Escanaba's proximity to croplands from its potential location was taken into account, ensuring efficient access to necessary markets. The relatively larger size of Escanaba's working population (civilian workforce of 55.3% in Delta County (US Census Bureau, 2018) compared to other cities in the UP also played a role in its selection. Avoiding a region with existing biomass utilization in northwestern UP (Baraga County) allowed for less competitive sourcing of biomass and addressed potential conflicts in resource allocation. In summary, the motivation behind selecting Escanaba was to establish a production facility in an area with a substantial procurement region for forest biomass, while leveraging existing forest product industries, transportation infrastructure, and workforce availability.

To select the locations for portable biochar production facilities, a systematic approach was taken, starting with the identified locations for stationary facilities in Grayling and Escanaba. The goal was to ensure that the relocation of portable units is not too far from these locations while minimizing overlaps with the procurement zones of each facility. This strategy aimed to cover the largest possible area within the procurement zones of the portable units. Through a trial-and-error process, multiple locations around Grayling in the LP and Escanaba in the UP were examined. Ultimately, the following locations: Cedar, Whitewater and Bearinger Townships were selected in Osceola, Grand Traverse, and Presque Isle counties in the LP, and Richmond, Felch and Lake Towns in Marquette, Dickinson, and Menominee counties in the UP. These selections were made to maximize the coverage of the procurement zones while minimizing the cost of relocating the portable units. In the UP, the forested land percentages for Marquette, Dickinson, and Menominee were 53.4%, 47.8%, and 24.1%, respectively, with each county having less than 10% cropland. In the LP, the forested land percentages of 39.7%, 40.7%, and 27.8 % with cropland acreages of 23.5%, 15.9%, and 11.8% for Osceola, Grand Traverse, and Presque Isle counties, respectively. By strategically placing the portable biochar production facilities in these counties, we aimed to efficiently cover a substantial area while making the best use of forested lands and minimizing the cost of delivering biochar to the croplands.

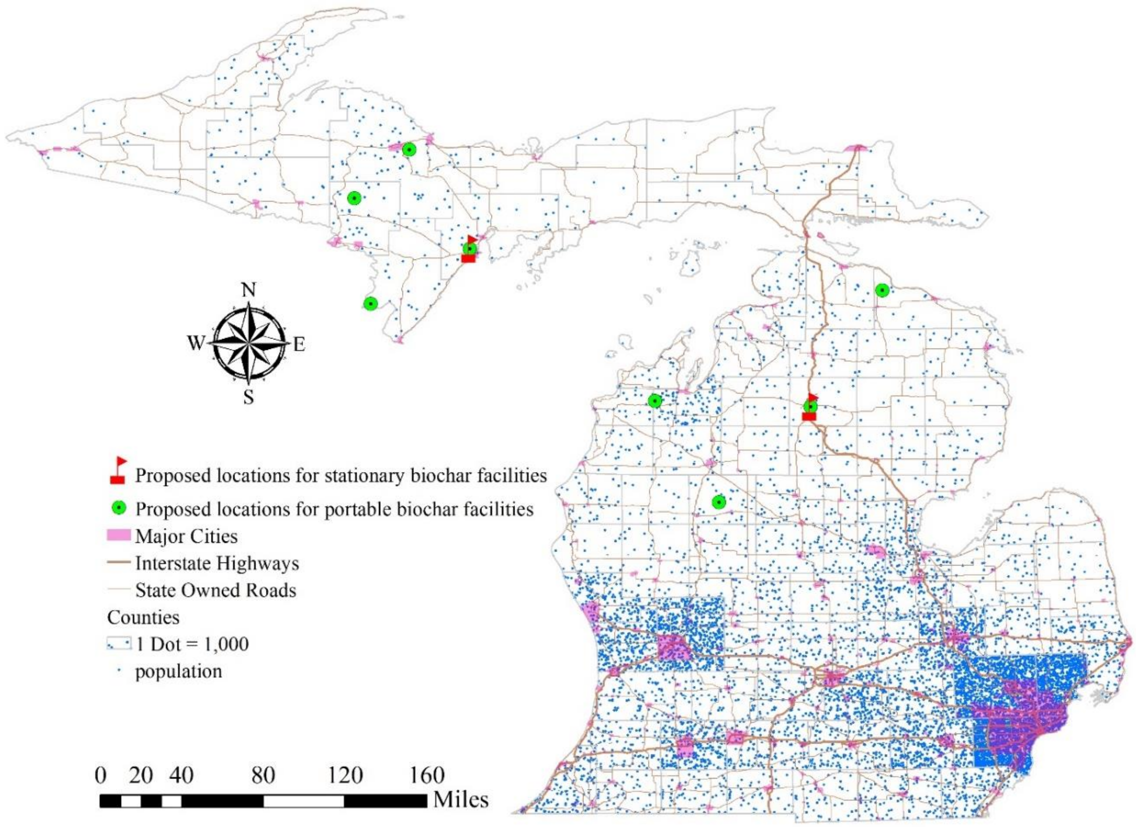

Figure 3.1 Major cities, highways, roads, and population in Michigan (State of Michigan (2023); CUBIT planning (2022)).

Procurement zones for biochar facilities at various delivered wood prices

The average delivered wood price is the summation of the stumpage (feedstock) cost, harvest cost, and transportation cost. For this analysis, the stumpage cost was assumed \$0/green t as the biochar producers procure non-merchantable logging residues with no landowner charge (Sahoo et al., 2019). Harvest costs comprise 35% of the delivered wood price (Steigerwaldt Land Services, 2015), leaving 65% of the delivered wood price for transporting forest biomass. Equation 2 was developed to estimate the hauling time from the average delivered wood price (Pokharel et al., 2023).

$$t=(0.5*((p-p_h-p_s)*w*60)/r) - t_l \quad 1$$

where t is hauling time (minutes), p is delivered wood price (\$/green t), p_h is harvest cost (\$/green t), p_s is stumpage price (\$/green t), w is average weight a truck can carry, r is trucking costs (\$/hour), t_l is loading & unloading time), $(p - p_h - p_s)$ in Equation 1 represents the available budget to compensate the transportation costs for hauling forest products.

The trucking costs involved in converting the delivered wood price into one-way haul time have been calculated by (Conrad, 2018) on an hourly basis after accounting for annual driving wages, benefits, maintenance, and insurance. Equation 2 shows all the equation parameters used for determining the trucking rates on an hourly basis.

$$r=C_t/((W_t*T_w)) \tag{2}$$

$$C_t= D_w+F+ T_p +T+ M_r+I+S+ S_p+ L_t+ E_s$$

where, r is per hour cost of operating a log truck, Ct is the annual cost of operating a logging truck, Wt is the total hours the truck is operated in a week, Tw is the total weeks the truck is operated in a year, Dw is annual driver wages, benefits, and overhead, F is annual fuel cost, Tp is annual truck payments, T is annual tires cost, Mr is maintenance and repair costs, I is Insurance (full coverage) costs, S is Shop (a centrally-located shop that allowed trucks to pick up backhauls and trucks frequently brought loaded trailers to the shop at the end of the day for a different truck to deliver to the mill the next day), Sp is support personnel wages, Lt is the cost of licenses, tags, etc., Es is the cost of employment screening (physicals, drug tests, etc.).

The one-way haul time corresponding to the delivered wood prices of biomass in Michigan 2020 (*baseline*) of $23.25/green t is 86 minutes (rounded off to ~ 90 minutes) assuming t_l =40 minutes, r = $90/hour, Wt = 40 hours for 50 weeks annually. We defined two additional delivered wood prices $29.54/green t (*20% above baseline*), and $18.46/green t (*20% below baseline*) to understand the sensitivity of changing transportation costs; a *20% below baseline* scenario corresponds to a one-way haul time of 60 minutes while a *20% above baseline* scenario corresponds to 120 minutes of one-way haul time.

The coordinates for latitude and longitude for each of the identified locations for biochar production were loaded onto ArcGIS to create a shapefile for the stationary and Portable facilities. The 'New Service Area' in the Network Analyst tool was used to create procurement zones from the one-way haul time obtained for each delivered wood price (60 minutes for $18.46/green t, 90 minutes for $23.25/green t, and 120 minutes for $29.54/green t). We mapped individual polygons or procurement areas for all of the locations identified for potential biochar production. We used the "Dissolve" function to merge all the individual polygons to find one polygon for UP and one polygon for LP for each delivered wood price. This approach determines the extent these facilities can economically travel to procure biomass at the given delivered wood prices.

Estimates of net annual woody biomass (NAWI) and potential supply of biochar

The procurement zones or polygons generated for stationary and portable facilities were overlaid with Forest Inventory & Analysis (FIA) data using the rFIA package (Stanke et al., 2020) on R to calculate the growth, removal, volume, and available biomass of growing stock. Net annual woody biomass increase (NAWI) (Goerndt et al., 2012) was calculated using Equation 3 for the procurement zones corresponding to delivered wood prices to assess the impact of changing prices on the availability of feedstock for different locations. NAWI is a measure used to estimate the annual potential supply of biomass after accounting for current removals that are available for procurement.

$$NAWI=((V_g - V_r))/V_t * W_b \qquad 3$$

where NAWI is the net annual woody biomass, V_g is the estimated annual net volume growth, V_r is the estimated annual volume of removal from the forest, and V_t is the estimated total live standing volume, W_b is the estimated total aboveground tree biomass. NAWI is a measure used to estimate the annual potential supply of biomass after accounting for current removals that are available for procurement.

After the NAWI was estimated, the potential annual supply of biochar was calculated using Equation 4.

$$Q_s=\beta * NAWI \qquad 4$$

Q_s is the potential supply of biochar, and β is the biomass to biochar yield. For each of the delivered wood prices, we calculated the potential biochar supply with a conversion yield of β= 0.350 or 35% (Mohan et al., 2014) for stationary facilities and β = 0.186 or 18.6% for portable units. An average conversion rate of different existing mobile units was considered in this study (Puettmann et al., 2020b) for portable facilities. Operational hours were held constant for both types of processing units to understand the responsiveness of different conversion yields and transportation costs. The biochar conversion yield varies significantly with changes in temperature and feedstock.

Potential demand for biochar in Michigan

To calculate the potential biochar demand, these procurement zones were overlaid with the land area cover of Michigan to determine the cropland area at different delivered wood prices. 'Cell statistics' in ArcGIS were used to convert the pixel count into area; the dimension of each pixel was 30m x 30m, making the area of each pixel to be $900m^2$. To optimize transportation costs, biochar would be applied to the cropland area within biochar service areas or delivery zones. The biochar service area is mapped using the same method outlined in Section 2.3 for fixed transportation cost of biochar such that it replaces $(p - p_h - p_s)$ in Equation 1. Values of $12.00/t, $15.11/t, and $19.20/t were used for the biochar transportation costs. The corresponding one-way haul time for the baseline of $15.11/t corresponds to 86 minutes while for $12.00/t it is 60 minutes and for $19.20/t it is 120 minutes. For the *baseline* scenario, biomass was procured at $23.25/green t and biochar will be applied at a transportation cost of $15.11/t (the one-way travel time for both is 91 minutes). Biochar will be applied locally to the region from where forest biomass was procured under the same cost constraints. Equation 5 was developed and used to calculate the potential annual biochar demand within these service areas for stationary and portable mobile processing facilities in Michigan.

$$Q_d = ((\alpha * A))/30 \qquad 5$$

Q_d is the potential annual local demand for biochar within the service area of biochar production facilities, α is the rate of biochar application per year over a 30-year rotation, and A is the total cropland area within the service area that will be treated with biochar.

The rate of application of biochar (α) varies regionally depending on the type of soil, however, we used an average value of 10 t/acre based on Thengane et al. (2021) as a constant rate of biochar application in Michigan. In this study, we considered a 30-year rotation of biochar application as a soil amendment, where biochar will be applied to the same unit of cropland area every 30 years.

Average price of biochar

Production costs involved for stationary and portable processing facilities were identified from the literature review. For stationary facilities, we considered a commercial reactor that can process 2205 t/day (2000 metric tonne/day) of biomass and account for total operating and capital investment costs of $15.39 million and $184.7 million, respectively (Brown et al., 2011b). On the other hand, for portable units, the processing capacity is 2.205 t/day (2 metric tonne/day) with operating costs being $1087.29/t biochar produced (Keske et al., 2020) and a capital cost of $576,250 for one portable unit (average of the capital cost obtained for portable units) (Delaney & Miles, 2019). The relocation cost of portable units every three months was also considered while calculating the MSPs, $37,538 annually (Bergman et al., 2022). All the obtained values have been adjusted for inflation (US BEA, 2022). The data obtained were adjusted for inflation for 2023 dollars (US BEA, 2023) and used to calculate the minimum selling price of biochar. (Delaney & Miles, 2019). The units were assumed to work 7.5 hours/day (averaged from data obtained from Bergman et al., (2022) and Delaney & Miles, (2019)) for 262 days/year (averaged from data obtained through Bergman et al., (2022), Keske et al., (2020) and (Delaney & Miles, 2019)).

3.3 RESULTS

Procurement zones for proposed biochar processing facilities in Michigan

The procurement zones for biomass expanded as the delivered wood price increased from *baseline* ($23.25/green t) to *20% above baseline* ($29.54/green t) and decreased from *baseline* ($23.25/green t) to *20% below baseline* ($18.46/green t), however, the expansion or reduction was not uniform (Figures 1 & 2 and Table 1). Optimizing transportation costs affords longer travel to collect forest biomass, however, the expansion in procurement area is not linear with the change in transportation cost. The procurement zones for portable units were larger compared to the stationary facilities for every delivered wood price in both UP and LP. This illustrates that portable units can procure a higher amount of biomass (feedstock) at the same delivered wood price or more forest biomass can be collected per unit of transportation cost and time. The mobility and relocation of portable units access more forest areas compared to stationary facilities. The procurement zones for portable units extended further to the western UP and branched out to adjoining counties in Wisconsin. A similar observation was made for the portable units in the LP that expanded further south unlike the procurement zones for stationary units at the corresponding delivered wood prices.

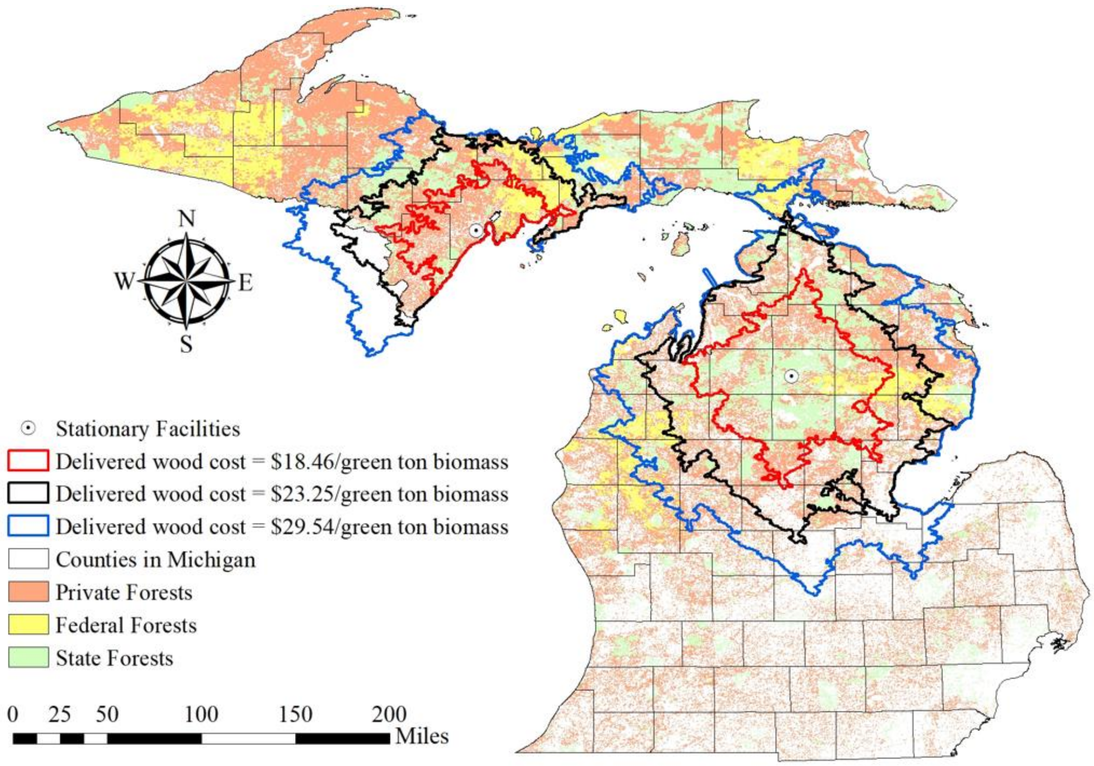

Figure 3.2 Procurement zones for potential stationary biochar processing facilities in Michigan (Sass et al., 2020)

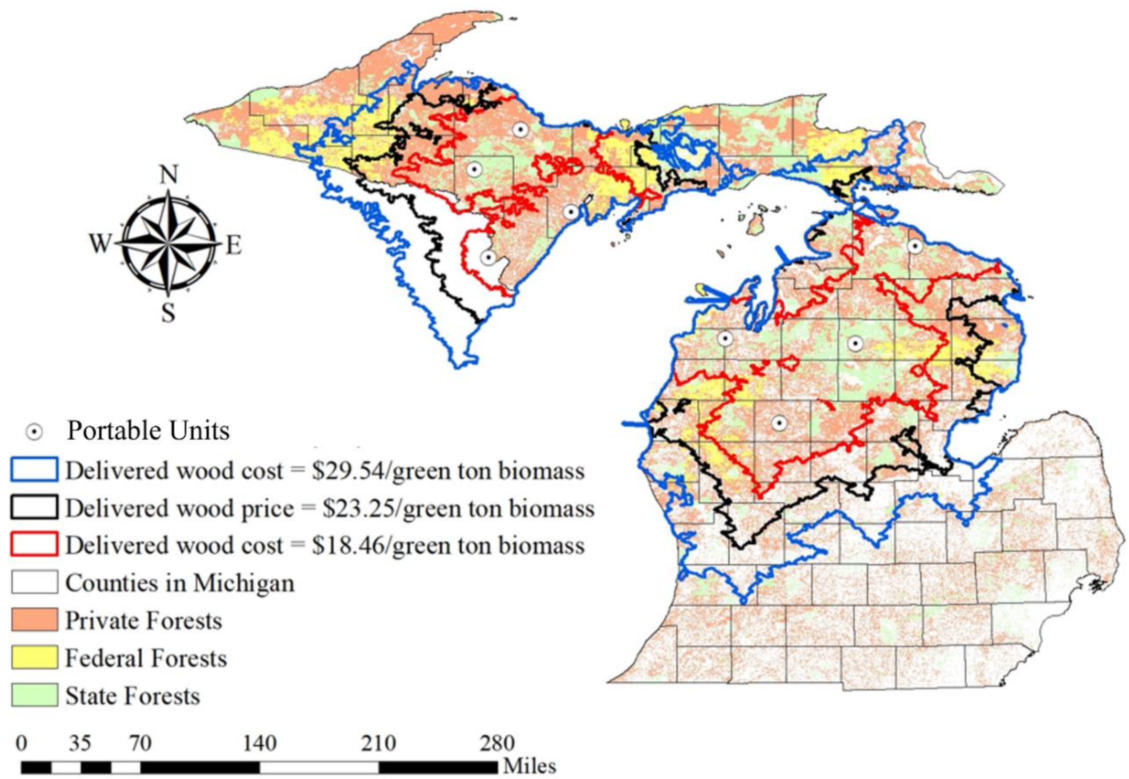

Figure 3.3 Procurement zones for portable biochar processing facilities in Michigan (Sass et al., 2020)

The model results show that there are 2.00 million acres of forestland for stationary facilities and 3.72 million acres of forestland for portable units at the baseline ($23.25/green t) delivered wood price in UP (Table 1). In LP, these figures were 4.12 million acres and 6.61 million acres for stationary and portable systems at the same delivered wood price, respectively. There was a 43% and 32% increase in forested lands in the UP for stationary and portable units, respectively, 20% above baseline ($29.54/green t). For LP, the same trend appears with an increase in forested lands as the delivered wood price increased. There were 6.31 million acres of forested land for stationary units and 8.31 million acres for portable units. When there was an increase in delivered wood price from 20% below baseline ($18.46/green t) to baseline ($23.25/green t), the area of forested lands increased by 1.20 million acres for stationary units and 1.39 million acres for portable units in the UP. For LP, the area of forested lands increased by 2.15 million acres and 2.62 million acres for stationary and portable units, respectively. Overall, there was an increase in forested lands for all cost scenarios with increasing delivered wood prices, where portable units were able to access more forested lands for biomass procurement at the same cost constraint. It should also be noted that in both stationary and portable units in LP, there were more forested lands accessible compared to the UP for all cost scenarios.

Table 3.1 Forest area within procurement zones for stationary and portable facilities in Michigan

Delivered wood price	Location in Michigan	Forests (Million acres)	
		Stationary	Portable
$18.46/green t *(20% below baseline)*	UP	0.80 (60%↓*baseline*)	2.33 (37%↓*baseline*)
	LP	1.98 (52%↓*baseline*)	3.99 (40%↓*baseline*)
$23.25/green t (*baseline*)	UP	2.00	3.72
	LP	4.12	6.61
$29.54/green t *(20% above baseline)*	UP	2.85 (43%↑*baseline*)	4.91 (32%↑*baseline*)
	LP	6.31 (53%↑*baseline*)	8.31 (26%↑*baseline*)

Net Annual woody biomass increase (NAWI)

In the UP, approximately 153 thousand tons (kt), 395kt, and 213 kt of NAWI were calculated from federal, private, and state-owned forests and were available at *baseline* ($23.25/green t) for a stationary facility, respectively (Table 2). On the other hand, in the LP, approximately 234 kt, 1,207 kt, and 450 kt of NAWI from federal, private, and state-owned forests were available at *baseline* ($23.25/green t) for a stationary facility. NAWI for private forests was calculated to be 182 kt in the UP, which was higher by 213 kt when there was an increase in delivered wood price from 20% below baseline ($18.46/green t) to baseline ($23.25/green t). However, from *baseline* ($23.25/green t) to *20% above baseline* ($29.54/green t), there was a 37% decline in NAWI for private forests, unlike all the other cases where there was an increase in NAWI with an increase in delivered wood price. The growth, removals, volume, and biomass available in each procurement zone increased with the increase in delivered wood costs, including the Growth to Removal or growth drain ratio (GRD), except for private forests at *baseline* ($23.25/green t) in the UP. The removals for the *20% above baseline* ($29.54/green t) scenario in the UP were higher in comparison to the *baseline* ($23.25/green t) scenario, causing the GRD to be smaller instead of being higher with the increase in delivered wood price. This is due to having more corporate private forests in the UP where growth and removals were almost equal, and removals were higher for commercial purposes in comparison to federal and state forests. For every type of forest ownership and cost condition, the NAWI calculated for LP was higher than the UP. The highest percentage increase occurred for federal forests in the LP when the delivered wood price increased from *baseline* ($23.25/green t) to *20% above baseline* ($29.54//green t) (130% more biomass was available for procurement if we can spend $6.29/green t more for transportation). In contrast, the lowest percentage increase occurred for federal forests in the UP (20% more biomass was available for procurement when there was an increase in delivered wood cost from *baseline* ($23.25/green t) to *20% above baseline* ($29.56/green t). The total NAWI for UP was higher for *baseline* and *20% above baseline* scenarios compared to the summation of NAWI from federal, private, and state forests; this happens due to procurement zones stretching out to Wisconsin. There was 761 kt biomass available for procurement at *baseline* ($23.25/green t) in the UP (an additional 99 kt can be procured from adjoining counties in Wisconsin). It was similar for a *20% above baseline* ($29.54/green t) case where 390 kt biomass can be procured from Wisconsin and 790 kt comes from the UP in Michigan.

For portable processing facilities, a similar trend was seen with the percentage increase in NAWI as the delivered wood price increased (Table 2). The only exception was for private forests when the procurement zone expands from *20% below baseline* ($18.46/green t) to *baseline* ($23.25/green t), where NAWI decreased by 10% due to excessive removals in the UP, primarily because of commercial logging operations by corporate foresters. At *baseline* ($23.25/green t), the difference between NAWI obtained from UP and LP is 206 kt for private forests, 370 kt for state forests, and 470 kt for federal forests; for all of them, the figures in LP are higher. Compared to the stationary units, portable mobile processing facilities had a higher NAWI, implying that more biomass was available for procurement through mobile units at all cost conditions. NAWI was higher in the LP from all types of forest ownership compared to the UP. In addition, there was no change in NAWI obtained from private forests when the procurement zone expanded from *baseline* ($23.25/green t) to *20% above baseline* ($29.54/green t) (the opposite was true for other cost and forest ownership types). This indicates that growth was equal to removals around this geographical location of portable facilities. The total NAWI for UP was higher for all cost conditions compared to the summation of NAWI from federal, private, and state forests because of procurement zones stretching out to Wisconsin. For example, at *20% above baseline* ($29.54/green t), NAWI from federal, state, and private forests was 1,220 *kt* in the UP while the total NAWI for this case was 2,266 kt (1,220 kt biomass can be procured in UP of Michigan and 1,046 kt can be procured from adjoining counties in Wisconsin). In this study, only the potential biomass supply from Michigan was considered, however, the total NAWI is an indicator of total biomass available in the UP for different price points within neighboring state counties.

Table 3.2 Net annual woody biomass increase (NAWI) for potential stationary and portable facilities in Michigan

Delivered wood price	Location	Net annual woody biomass increase (NAWI) by Forest Ownership (thousand tons, kt)							
		Stationary				Portable			
		Federal	Private	State	Total	Federal	Private	State	Total
$18.46/ green t *(20% below baseline)*	UP	45 (71% $\downarrow_{baseline}$)	182 (54% $\downarrow_{baseline}$)	27 (87% $\downarrow_{baseline}$)	254	70 (61% $\downarrow_{baseline}$)	220 (-10% $\downarrow_{baseline}$)	320 (26% $\downarrow_{baseline}$)	682
	LP	58 (75% $\downarrow_{baseline}$)	399 (67% $\downarrow_{baseline}$)	300 (33% $\downarrow_{baseline}$)	760	190 (71% $\downarrow_{baseline}$)	1330 (41% $\downarrow_{baseline}$)	630 (21% $\downarrow_{baseline}$)	2,140
$23.25/ green t (*baseline*)	UP	153	395	213	860	180	200	430	1,282
	LP	234	1207	450	1892	650	2,260	800	3,698
$29.54/ green t *(20% above baseline)*	UP	183 (20% $\uparrow_{baseline}$)	249 (37 % $\downarrow_{baseline}$)	358 (68% $\uparrow_{baseline}$)	1180	530 (194% $\uparrow_{baseline}$)	200 (0% $\uparrow_{baseline}$)	490 (14% $\uparrow_{baseline}$)	2,266
	LP	538 (130% $\uparrow_{baseline}$)	1,944 (61% $\uparrow_{baseline}$)	778 (73% $\uparrow_{baseline}$)	3266	840 (29% $\uparrow_{baseline}$)	2,970 (31% $\uparrow_{baseline}$)	980 (23% $\uparrow_{baseline}$)	4,795

Note: $\downarrow_{baseline}$ indicates a decrease from baseline, and $\uparrow_{baseline}$ indicates an increase from baseline.

Potential annual biochar supply in Michigan

There was an increase in potential annual biochar supply with the increase in delivered wood prices from *baseline* ($18.46/green t) to *20% above baseline* ($29.54/green t) for both stationary and Portable facilities (Figure 3). This occurs because biomass availability increases when biomass suppliers can spend more on transportation. At the delivered wood price of *baseline* ($23.25/green t), stationary, and portable units in the LP were able to produce 331 kt and 356 kt (a difference of 25 kt). It should be noted that although more biomass was being procured by portable facilities, their lower conversion yield (18.6%) made them fall short during the biomass-to-biochar conversion process. The highest annual potential biochar supply was from stationary units in the LP at 572 kt when *20% above baseline* ($29.54/green t) was paid to procure forest biomass, which was 462 kt for Portable units at the same price for biomass. The number was 3.85 times lower for the UP at the same cost for portable facilities. Overall, LP had a higher potential biochar supply on average compared to the UP at all delivered wood prices of biomass for both stationary and portable facilities in Michigan. For private forests in UP, the ratio obtained for GRD decreases when there was an expansion of procurement zones from *20% below baseline* ($18.46/green t) to *baseline* ($23.25/green t), unlike all the other cost conditions where this ratio increases. These removals were higher compared to the other cost conditions.

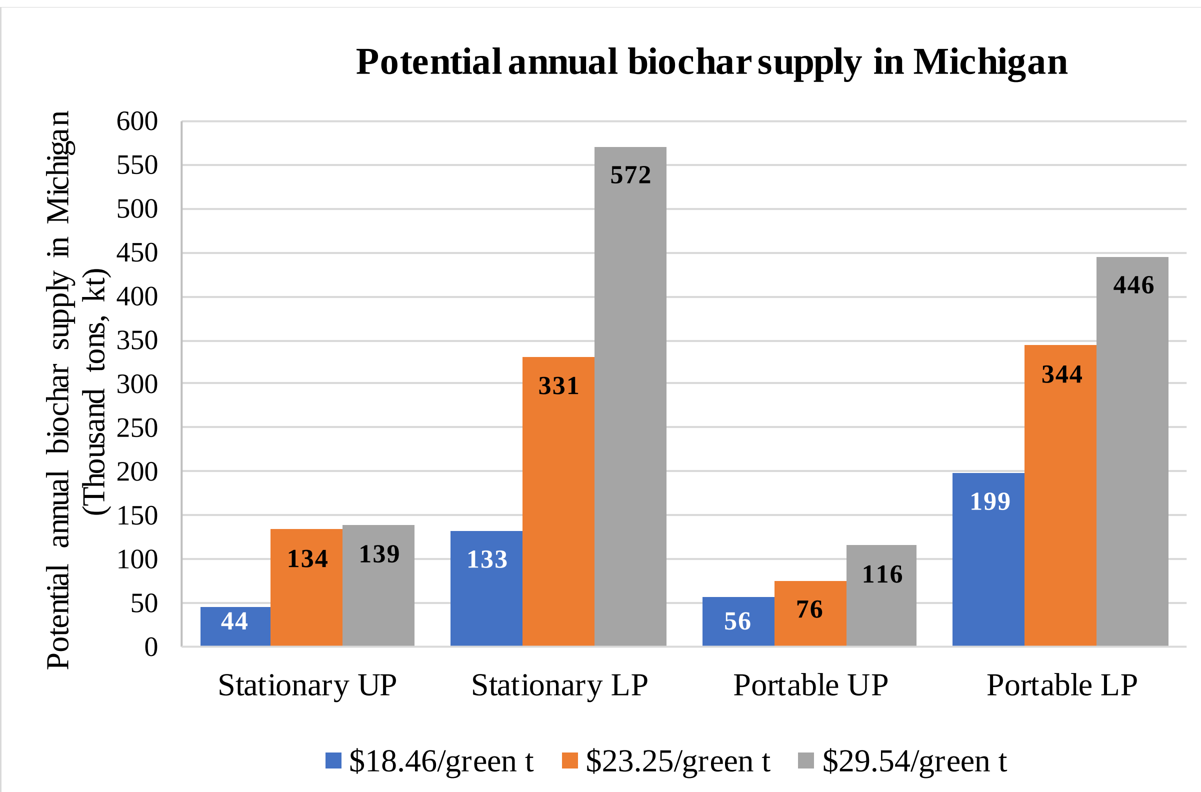

Figure 3.4 Potential annual biochar supply for stationary and portable processing facilities in Michigan

Application areas for biochar application as a soil amendment in Michigan

There was an expansion in the application areas for biochar with the increase in transportation costs, i.e., the more spent on transportation, the further biochar can be hauled to agricultural lands for application (Figures 4, 5, and Table 3). It should be noted that biomass was procured from the forests within these same cost boundaries and biochar is being applied to the cropland within these respective boundaries. For baseline, ($15.11/t), the cropland area in the UP was 116 k acres for stationary units, which was 2.12 times higher for portable units. For the LP under the same cost condition, the figures were higher at 890 k acres and 1,599 k acres for stationary and portable units, respectively. There was a 96% increase in cropland area when the transportation cost increased from baseline ($15.11/t) to 20% above baseline ($19.21/t) for stationary facilities in the UP, whereas it was 62% for portable units. The largest percentage increase in cropland area was observed at 116% for stationary units in LP for 20% above baseline ($19.21/t). In contrast, the smallest percentage increase was noticed for 20% below baseline ($12/t) at 43% for stationary units in the UP. The application areas for biochar are larger for portable processing facilities compared to the stationary ones, implying that there was a larger accessibility to cropland areas through portable facilities for the same amount of money spend on transporting biochar. This happens due to the mobility of portable units to different geographical locations where they have larger access to forest biomass. Stationary units are bound to utilize the resources available within a certain geographical boundary throughout the year, unlike portable units. It should also be noted that the cropland area in the LP was larger compared to the UP for every cost condition, suggesting that the potential biochar demand as a soil amendment will be higher in LP.

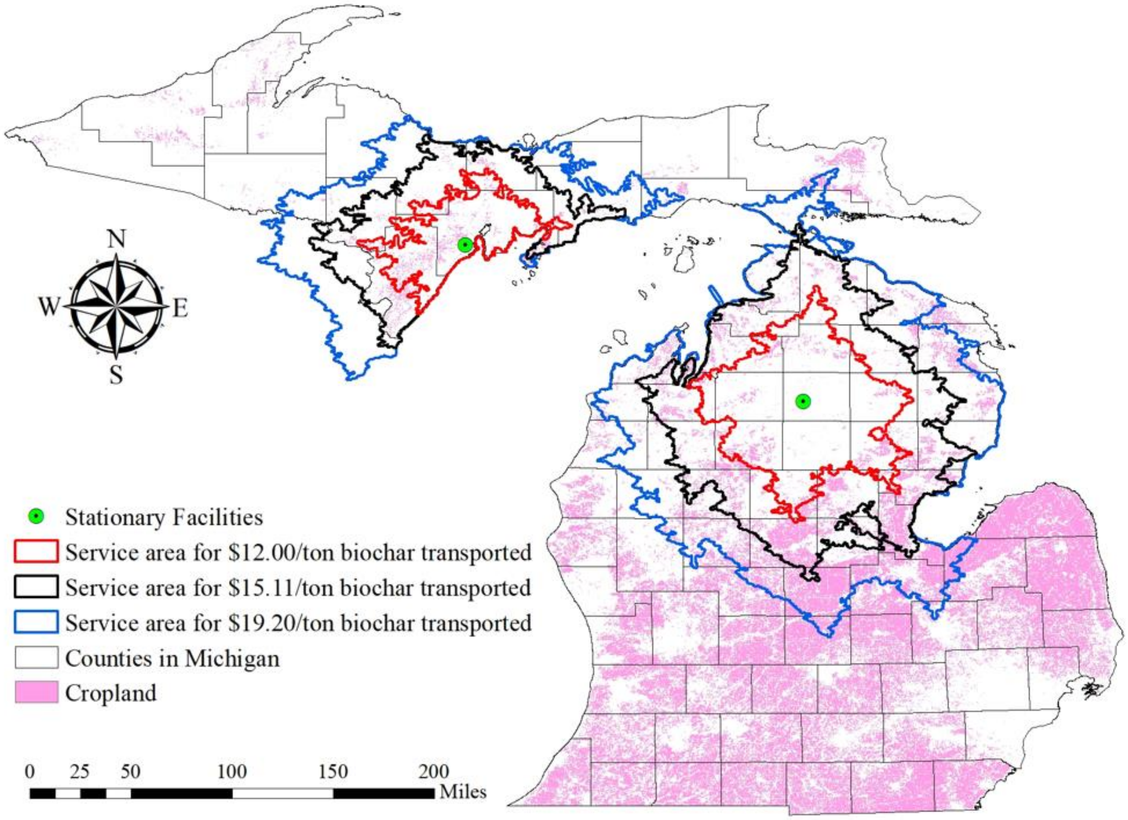

Figure 3.5 Application area for biochar application through stationary facilities in Michigan (USGS, 2019).

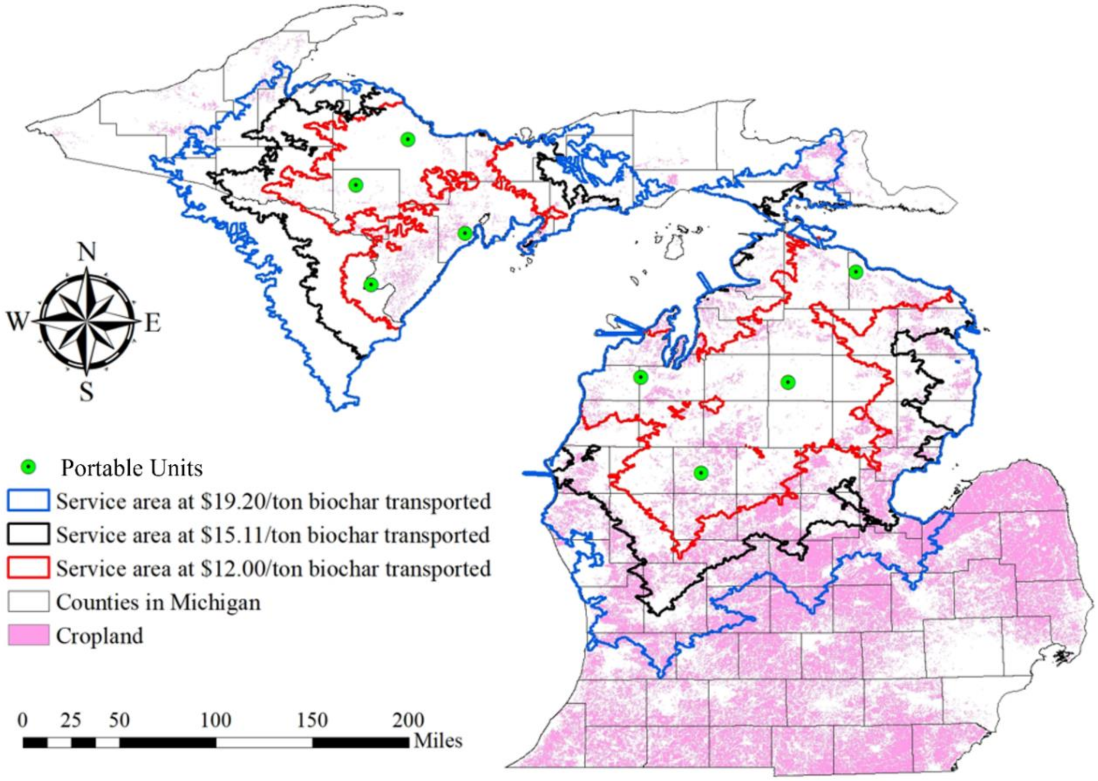

Figure 3.5 Application Area for biochar application through portable facilities in Michigan (USGS, 2019).

Table 3.3 Cropland area within procurement zones for stationary and portable processing facilities in Michigan

Transportation cost of biochar	Location in Michigan	Area of Cropland within the service area (1000 (k) acres)	
		Stationary	Portable
20% below baseline ($12.00/t)	UP	66 (43%↓*baseline*)	126 (49%↓*baseline*)
	LP	176 (80%↓ *baseline*)	606 (62%↓*baseline*)
baseline ($15.11/t)	UP	116	246
	LP	890	1,599
20% above baseline ($19.21/t)	UP	227 (96%↑*baseline*)	399 (62%↑*baseline*)
	LP	1,922 (116%↑*baseline*)	3,040 (90%↑*baseline*)

Potential annual biochar demand in Michigan

There was an increase in potential annual biochar demand as the service area expanded with an increase in the available budget to compensate for transportation costs; the trend remained the same for both stationary and portable facilities in UP and LP (Figure 3.8). A minimum of $6.0/t needs to be spent for transporting biochar to agricultural lands. The range of transportation costs estimated was between $6.0/t and $40.8/t for biochar delivery to agricultural lands. The largest potential annual biochar demand corresponded with largest service area for portable units in the LP at approximately 5,900 kt for the transportation cost of $40.8/t. At the same transportation cost, this figure was lower by 1,370 kt for stationary units in the LP. For stationary units, the potential annual biochar demand in UP at biochar transportation cost of $40.8/t was 4530 kt, while it was lower by 2673 kt for stationary units in LP. There was a higher potential annual biochar demand in LP compared to the UP for a service area with the same cost for both stationary and portable facilities. For example, through portable mobile units, 2.47 times more biochar was demanded in the LP compared to the UP for a service area with $40.8/t in transportation costs. For stationary facilities, it was 2.44 times higher in the LP compared to UP at the same price. Overall, when both these systems are compared, the potential annual demand within the application area at the same cost, portable units, was higher compared to the stationary facilities.

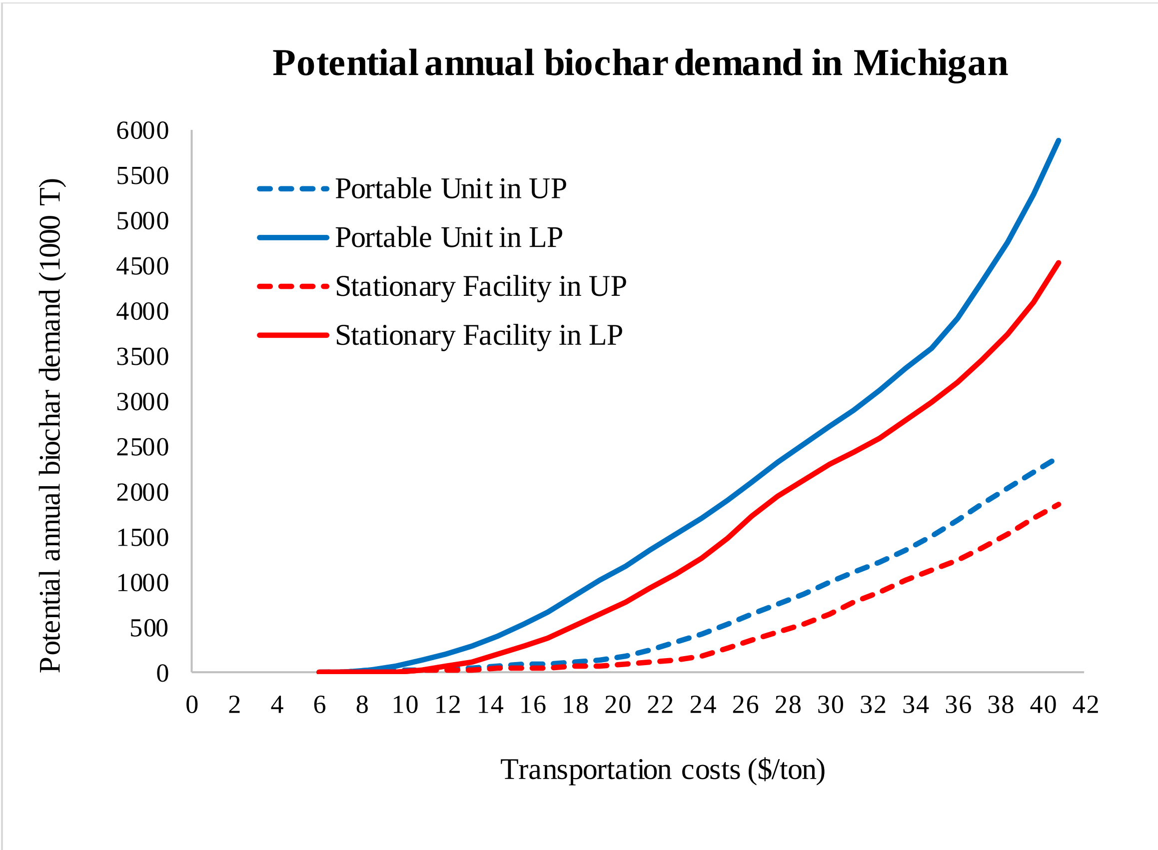

Figure 3.6 Potential annual biochar demand for service areas corresponding the transportation costs in Michigan

Potential annual biochar demand vs supply in Michigan

Since the same application area was used for procurement of forest biomass as well as biochar application, a demand and supply ratio could inform on resource availability or limitations. When the demand-to-supply ratio is more than 1.0, the potential demand is higher than the potential supply within that respective service area for biochar. For example, for the *baseline*, stationary units in the LP had a demand-to-supply ratio of 0.90, implying that there was a surplus of 10% in biochar supply. It also shows that 90% of the biomass procured at *baseline* can be utilized for biochar production and applied within the service area supported by a transportation cost of $15.11/t for biochar. However, for *baseline* biomass procurement and biochar transportation, portable units in the UP had a demand-to-supply ratio of 1.04, implying that there was a deficit of 4% in biochar supply. It also shows that all of the biomass procured at *baseline* ($23.25/t) can be utilized for biochar production and applied within the service area supported by a transportation cost of $15.11/t for biochar, and there will be still more demand for biochar. For *20% below baseline* ($12/t), there was potential biochar demand of 50% for stationary and 72% for portable units (1.44 times higher) in the UP; a similar observation was noticed for LP where the biochar demand was 2.23 times higher for portable units. For *20% above baseline* ($19.21/t), through stationary units, there would be a 45% surplus of biochar whereas with the portable units, there would be a deficit of 11%. In our study, the demand for biochar increased with the increase in delivered wood prices since we only considered calculating potential biochar demand using the cropland within each application area. The demand in the application area supported by *20% above baseline* ($19.21/t) in transportation costs for portable units required 119% more biochar than the existing supply in the LP; this was the highest demand-to-supply ratio obtained under all cost constraints. This also indicates that the service area can be smaller than the feedstock procurement area to meet the demand. The demand-to-supply ratio for portable units was higher for all cases compared to stationary units, suggesting that we can meet more of biochar's demand as a soil amendment through the former option.

Table 3.4 Potential annual biochar demand, supply, and its ratio under different cost scenarios in Michigan

Costs	Facility Location	Demand (*kt*)		Supply (*kt*)		Ratio of Demand: Supply	
		Stationary	Portable	Stationary	Portable	Stationary	Portable
20% below baseline ($12.00/t)	UP	22	42	44	58	0.50	0.72
	LP	59	202	133	206	0.44	0.98
baseline ($15.11/t)	UP	39	82	134	79	0.29	1.04
	LP	297	533	331	356	0.90	1.50
20% above baseline ($19.21/t)	UP	76	133	139	120	0.55	1.11
	LP	641	1013	572	462	1.12	2.19

Production unit requirement to fulfill the potential biochar demand in Michigan

For the service area of biochar application with 15.11/t in transportation cost, two stationary units would be sufficient to fulfill the demand in LP while it would require 596 portable facilities (298 times higher). On the other hand, in the UP, 1 unit would suffice against 97 portable units. For all service areas under all transportation costs, the number of portable units required for biochar production is higher compared to stationary units. A higher number of portable units are required to operate in parallel throughout the year to fulfill the potential demand. A maximum of 3 units would be required in the LP at the highest cost of *20% above baseline* ($19.20/t) of biochar transported. To fulfill the potential biochar demand in the UP, fewer units are required for both stationary and portable processing facilities. For portable facilities, the unit requirement varies between 97 and 772 between *20% below baseline* ($12.11/t) and *20% above baseline* ($19.20/t) in transportation costs for biochar from the potential facility to the farmlands. For UP, regardless of the potential biochar demand, one unit would be sufficient to produce the required amount however, for LP, there is an increase in the required number of units with the increase in transportation costs.

Table 3.5 Production capacity requirement to fulfill potential biochar demand in Michigan

Service area for biochar application	Location	Required number of Facilities		Ratio of portable: stationary units
		Stationary	Portable	
20% below baseline ($12.00/t)	UP	1	97	97
	LP	1	345	345
Baseline ($15.11/t)	UP	1	132	132
	LP	2	596	298
20% above baseline ($19.20/t)	UP	1	200	200
	LP	3	772	257

Potential costs for fulfilling potential biochar demand in Michigan

For the service area supported by *baseline*, the potential minimum selling price (MSP) of biochar is $1,606/t in the UP and $1,340/t in the LP for stationary facilities ($1,473/t on average). The MSP in LP for stationary units at *baseline* was lower by $267/t compared to the UP. For portable units, the MSPs are higher than stationary units, however, the difference in MSPs for portable units for UP and LP had only a $1/t difference for every cost scenario. Although UP had lower biomass procurement per unit transportation cost, the MSPs in UP and LP for portable units were approximately the same per ton biochar of produced. The MSP of biochar for stationary units in both UP and LP decreases with the increase in the service area for biochar application, hence the demand for biochar, indicating that they can achieve economies of scale with a corresponding increase in the amount of biochar produced. However, for portable facilities, the opposite trend was observed and there was an increase in MSP of biochar with the increase in service area for biochar application. The increase in biochar demand increases the number of units required to fulfill the demand, essentially increasing the costs involved. Small capacity and low conversion yields make the MSP for portable facilities higher compared to stationary ones. The MSP for stationary facilities is between $1,234/t and 4,353/t biochar, whereas it was in the range between $2,296/t and $2,422/t biochar for portable facilities in Michigan. The MSP range for stationary facilities is larger ($3,172/t biochar) compared to portable units ($126/t biochar), telling us that the former system gives us more flexibility in customizing plant sizes, and production capacities according to desired profit margins, unlike the latter. This also implied that portable units are not suitable if we are trying to achieve economies of scale. Overall, the LP has a lower MSP compared to the UP for both stationary and portable units. Having a higher potential biochar supply in the LP helps bring the cost down for both these systems.

Table 3.6 Minimum selling price of biochar (MSP) for stationary and portable facilities in Michigan

Costs	Facility Location	Minimum Selling Price of Biochar ($/ton)	
		Stationary	Portable
20% below baseline ($12.00/t)	UP	4,353	2,296
	LP	1,583	2,295
Baseline ($15.11/t)	UP	1,606	2,351
	LP	1,340	2,350
20% above baseline ($19.20/t)	UP	1,592	2,423
	LP	1,234	2,422

Note: The minimum selling price of biochar includes the transportation cost of low-value biomass, production costs (capital costs, equipment costs, operational costs, labor costs) and the transportation cost of biochar to agricultural lands in Michigan. The values have been rounded off to the closest integer.

3.4 DISCUSSION

Managing unused forest biomass can be an economic and environmental challenge. The estimation of the economic availability of forest biomass from different forest ownership can help investors, funding agencies, entrepreneurs, and biochar distributors direct their investment more efficiently. The study outcomes have identified that an increase in biomass availability is not uniform with the increase in delivered wood price for biomass. Spending more on transportation costs will not always ensure getting access to more biomass for all geographical locations. This is due to the growth and removal volume for forests at one particular location; for example, commercial logging operations conducted in the UP have higher removals in comparison to LP for industrial private forest ownerships. With the expansion in the procurement area, forest biomass availability might not increase due to high removal rates. Around 29% of Michigan belongs to UP, which possesses 45% of the forests in the state, while southern LP being the largest region (14.8 million acres) has only 18% of forests and northern LP has 37% forested lands (Pugh, 2018). The proposed biochar facilities in UP had more forest cover around them compared to the facilities in northern LP. However, when overlaid with the cost-optimal procurement areas, LP is better equipped to procure biomass due to having better infrastructure and road network compared to the UP. It should be noted that biomass can be procured from adjoining counties in Wisconsin for both stationary and portable units in UP, unlike LP. The amount of biochar required as a soil amendment in UP is lower relative to LP and indicates that there is a potential biochar surplus in UP. In addition, LP has a higher potential demand for biochar compared to UP as it has a higher cropland acreage, hence the demand is higher. When it comes to biochar application, portable units can cover a larger proportion of cropland at the same transportation cost as the production unit moves around through a year.

The biomass supply through portable units is larger compared to stationary ones for all cost scenarios in both UP and LP. It is a better choice to use portable units for procuring biomass since it can procure more biomass at the same cost. This is due to relocating every three months between counties and having the flexibility to conduct biomass procurement operations at different locations expanding the procurement area. However, the conversion yields of portable facilities fall short despite having more biomass going into the conversion process. This suggests that to meet the same potential biochar demand, a higher number of portable units as well as a larger volume of forest biomass are required compared to the stationary units, because of the former's lower conversion rate and processing capacity. Even though a single portable unit is around $262,384, with the increased number of units to meet the same level of production as stationary, portable units require a higher initial capital investment if the same potential biochar demand is to be met. Although, when considering a new forest product in the market with low demand, portable units can be better options as they can be scaled up gradually depending on the local demand for biochar. It would help minimize financial risks, unlike stationary units where a potential biochar surplus could occur in a market with low demand.

The MSP of stationary units in both UP and LP can achieve economies of scale under all cost scenarios however, for portable units, it has not been possible. The average price of biochar produced commercially was $2,580/t in 2019 (Farm Energy, 2019). The average MSP between UP and LP was $1,370/t biochar for stationary facilities at *baseline* whereas it was approximately $1617/t biochar for portable units (higher by $247/t). The low conversion yields and requirement of the increased number of units to fulfill the biochar demand make portable systems less economically viable if the same level of production has to be met. Regardless of the procurement location, the MSP for stationary units is lower than the portable mobile units and the average price of biochar in 2019. The provision of carbon credits for biochar application can help drive its demand in the local economy and attract more regional investment. The price of biochar credits can vary between $82/t and $544/t biochar, with the majority being in the range of $86/t and $113/t (Elias et al., 2021). If 10 t/acre of biochar is applied on agricultural land, carbon credits for carbon storage from biochar would be worth $860-$1,130, eventually helping to bring down the MSP for both stationary and portable units. In addition, government grants and subsidies provide up to $5100/acre for biochar production from forest residues (Sahoo et al., 2019), and enrollment of farmers in such programs can help further in bringing down biochar production costs.

To reduce the high cost of biochar, one approach could be to explore the co-production of biofuel and biochar by utilizing mill residues in existing bioenergy facilities in Michigan. Biofuel, such as green diesel, sustainable aviation fuel, and green bunker fuel, is the primary product, while biochar would be the secondary product used for soil amendment. This avoids attributing all of the production costs to biochar, as biofuel is the primary product. With existing policies targeted toward energy security objectives, the global demand for biofuels is expected to increase by 11% by 2024 (International Energy Agency, 2023). Directing investment toward coproduction can make biochar investments economically viable where programs such as the Biorefinery Assistance Program (Pourhashem et al., 2019) could help; however, the provision of government subsidies and grants may entice the market to ensure long-term commercial viability for biochar production in Michigan. In addition, conducting a life-cycle assessment will help evaluate the reduction (or increase) in greenhouse gas emissions for biochar production from forest biomass and application in local farms. Calculating the environmental impacts during cultivation, harvest, chipping, drying, transportation, pyrolysis, and application of biochar to cropland can help regional stakeholders identify processes in the supply chain where more innovation and optimization are required. It will also help in developing regional policies that include providing biochar carbon credits and biochar tax rebates.

Through this assessment, decision-makers have more information about feedstock availability at different delivered wood prices in Michigan. Optimizing transportation costs will encourage local biomass procurement with the opportunity to apply biochar locally in agricultural lands. The study has quantified the potential supply and demand of biochar for different locations in UP and LP, giving investors more information about biomass availability for biochar production. Using unused forest biomass for biochar production can help boost the rural economy with potential job creation in addition to sequestering carbon through agricultural practices. The use of biochar as a soil amendment can be a path towards obtaining carbon credits, and tax rebates for stakeholders in agriculture while ensuring forest health through using non-merchantable timber and wood products. The information will help stakeholders identify and use existing natural resources towards building a circular economy in Michigan.

The scope of the study deals with collecting biomass from forests and applying biochar to the cropland that lies within the same procurement zone or service area for all cost scenarios. We investigated the maximum amount of biomass that can be available under the transportation cost optimization approach by considering $0/green t for stumpage on biomass only, which is the first limitation of this study. There will be costs associated with compensating the landowners if the demand and competition for biomass increases in a region. This will impact the percentage of delivered wood price that can be used as transportation cost and compress the procurement zones and services areas generated at each cost scenario. The scenario of excess biochar was not examined in the study (second limitation). Neither was bringing additional biochar when the supply is not enough to apply at the rate of 10 t/acre (third limitation). A surplus of biochar would indicate that the production capacity of the facilities can be downsized within that procurement zone or service area while a shortage would indicate the opposite. To overcome these challenges, it is important to understand the perspective of landowners and farmers regarding biochar production, including the type of incentives that could make biochar production lucrative to them. A survey could be conducted to address this issue and to identify the farmers who would be willing to apply biochar as a soil amendment. Moreover, this study quantifies biochar demand with a consistent application rate of 10 t/acre over a 30-year rotation, however, it did not account for the type of soil or crops grown on the agricultural lands to customize the biochar application rate. These demand and supply surveys will help answer these questions and further categorize potential production capacities required regionally.

3.5 CONCLUSION

The study helps us bridge the knowledge gap on unused forest biomass procurement and utilization for biochar production in Michigan. The novelty of this study lies in optimizing transportation costs for biochar production and quantifying its utilization as a soil amendment in UP and LP. The forest biomass in UP is less accessible compared to the LP due to the latter having a more robust infrastructure and a better road transportation network; LP has a higher potential supply and demand for biochar under all cost scenarios. A minimum of $6 has to be spent to transport biochar to agricultural lands in both the UP and LP. Although portable units can procure a higher amount of biomass at the same cost, their lower conversion yields compared to stationary units, make them less efficient economically. To compensate for the low conversion yield, a higher number of portable units are required to fulfill the potential biochar demand, making it difficult to achieve economies of scale, unlike the stationary units. Stationary units can procure more biochar and apply it to a larger proportion of cropland area compared to portable units. Stationary units are also able to achieve economies of scale unlike the portable units and have a lower MSP of biochar under all cost scenarios. A potential market for forest biomass in Michigan will help policymakers to develop forest management plans for resilient and healthy forests and natural resource-based climate strategies across the Great Lakes region. It will inform stakeholders in agriculture and forestry to collaborate in optimizing the supply chain of biomass and biochar.

REFERENCES

American Biochar Company. (2016). *Products*. American Biochar Company. Available on: https://ambiochar.com/products/#VitalBlend. Last accessed on 8th August 2023.

Bergman, R., Sahoo, K., Englund, K., & Mousavi-Avval, S. H. (2022). Lifecycle assessment and techno-economic analysis of biochar pellet production from forest residues and field application. *Energies*, *15*(4), 1559.

Brown, T. R., Wright, M. M., & Brown, R. C. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining*, *5*(1), 54-68.

Conrad IV, J. L. (2018). Costs and challenges of log truck transportation in Georgia, USA. *Forests*, *9*(10), 650.

CUBIT planning.(2022). *Michigan Cities by Population*. Michigan Demographics by CUBIT. Available on : https://www.michigan-demographics.com/cities_by_population. Last accessed on 8th August 2023.

Delaney, M., & Miles, T. (2019). Economics of mobile and stationary biochar production systems using juniper feedstocks in Oregon. *Corvallis, OR: USDA–ARS, Oregon State University*.

Dewitz, J., and U.S. Geological Survey, 2021, National Land Cover Database (NLCD) 2019 Products (ver. 2.0, June 2021): U.S. Geological Survey data release.

Eggink, A., Palmer, K., Severy, M., Carter, D., & Jacobson, A. (2018). Utilization of wet forest biomass as both the feedstock and electricity source for an integrated biochar production system. *Applied Engineering in Agriculture*, *34*(1), 125.

Elias, M., Hunt, J., Remucal, J., Saksa, P., & Sanchez, D. (2021). *Biochar Carbon Credit Market Analysis: Examining the potential for coupled biochar and carbon credit production from wildfire fuel reduction projects in the Western U.S.* Blue Forest Conservation, 44pp. Available on https://pacificbiochar.com/wp-content/uploads/BiocharCarbonCreditAnalysis-BFReports20221.pdf. Last accessed on 8th August 2023.

ESRI. (2017). North American Detailed Streets. ESRI. Available on http://www.arcgis.com/home/item.html?id=f38b87cc295541fb88513d1ed7cec9fd. Last accessed on 8th August 2023.

Farm Energy. (2019). *Biochar: Prospects of Commercialization*. USDA National Institute of Food and Agriculture. Available on : https://farm-energy.extension.org/biochar-prospects-of-commercialization/. Last accessed on 8th August 2023.

Forest Inventory and Analysis Database. (2023). *FIA DataMart.* USDA Forest Service. Available on https://apps.fs.usda.gov/fia/datamart/datamart.html. Last accessed on 8th August 2023.

Forest Inventory and Analysis Database. (2023). *NLCD 2019 Land Cover (CONUS)*. Multi-Resolution Land Characteristics Consortium. Available on https://www.sciencebase.gov/catalog/item/604a4fb1d34eb120311b0039. Last accessed on 8th August 2023.

Goerndt, M. E., Aguilar, F. X., Miles, P., Shifley, S., Song, N., & Stelzer, H. (2012). Regional assessment of woody biomass physical availability as an energy feedstock for combined combustion in the US northern region. *Journal of Forestry*, *110*(3), 138-148.

IEA (2023), *Renewable Energy Market Update - June 2023*, IEA, Paris, License: CC BY 4.0. Available on : https://www.iea.org/reports/renewable-energy-market-update-june-2023. Last accessed on 8th August 2023.

Keske, C., Godfrey, T., Hoag, D. L., & Abedin, J. (2020). Economic feasibility of biochar and agriculture coproduction from Canadian black spruce forest. *Food and energy security*, *9*(1), e188.

Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *177*(5), 651-670.

Mittlefehldt, S., Bunting, E., Huff, E., Welsh, J., & Goodwin, R. (2021). New Methods for Assessing Sustainability of Wood-Burning Energy Facilities: Combining Historical and Spatial Approaches. *Energies*, *14*(23), 7841.

Mohan, D., Sarswat, A., Ok, Y. S., & Pittman Jr, C. U. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. *Bioresource technology*, *160*, 191-202.

Pokharel, R., Latta, G., & Washington, C. (2023). Identifying Economically Feasible Priority Landscape Areas in Idaho for Funding Assistance Programs. *Journal of Forestry*, *121*(2), 145-156.

Pourhashem, G., Hung, S. Y., Medlock, K. B., & Masiello, C. A. (2019). Policy support for biochar: Review and recommendations. *GCB Bioenergy*, *11*(2), 364-380.

Puettmann, M., Sahoo, K., Wilson, K., & Oneil, E. (2020). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production*, *250*, 119564.

Pugh, S. A. (2018). Forests of Michigan, 2017.

Sahoo, K., Bilek, E., Bergman, R., & Mani, S. (2019). Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. *Applied Energy*, *235*, 578-590.

Sass, E. M., Butler, B. J., & Markowski-Lindsay, M. Estimated Distribution of Forest Ownerships Across the Conterminous United States, 2017.

Stanke, H., Finley, A. O., Weed, A. S., Walters, B. F., & Domke, G. M. (2020). rFIA: An R package for estimation of forest attributes with the US Forest Inventory and Analysis database. *Environmental Modelling & Software*, *127*, 104664.

State of Michigan. (2023). *Cities.* GIS Open Data. Available on : https://gis-michigan.opendata.arcgis.com/datasets/cities-1/explore?location=67.692232%2C48.118823%2C7.00. Last accessed on 8th August 2023.

State of Michigan. (2023). *State Owned Roads (v17)*. GIS Open Data. Available on : https://gis-michigan.opendata.arcgis.com/datasets/cities-1/explore?location=67.692232%2C48.118823%2C7.00. Last accessed on 8th August 2023.

Steigerwaldt Land Services. (2015). *Wood Supply Chain Component Costs Analysis: A Comparison of Wisconsin and U.S. Regional Costs-(Data Period: Q3 2013 through Q2 2015, 2015 Update)*. Steigerwaldt Land Services, Inc. Available on https://councilonforestry.wi.gov/Documents/PracticesStudy/ProjectReportFall2015.pdf. Last accessed on 8th August 2023.

Thengane, S. K., Kung, K., Hunt, J., Gilani, H. R., Lim, C. J., Sokhansanj, S., & Sanchez, D. L. (2021). Market prospects for biochar production and application in California. *Biofuels, Bioproducts and Biorefining*, *15*(6), 1802-1819.

US BEA. (2023). *Inflation Calculator.* US Inflation Calculator (a Coin News Media Group Company). Available on https://www.usinflationcalculator.com/. Last accessed on 8th August 2023.

U.S. Census Bureau. (2022). *Michigan Civilian labor force participation rate, age 16 years and over by County.* Index mundi (US Census Bureau Programs). Available on : https://www.indexmundi.com/facts/united-states/quick-facts/michigan/civilian-labor-force-participation-rate#map. Last accessed on 8th August 2023.

US Census Bureau, D. of C. (2021). *TIGER/Line Shapefile, 2019, state, Michigan, Primary and Secondary Roads State-based Shapefile*. U.S. General Services Administration Technology Transformation Services. Available on https://catalog.data.gov/dataset/tiger-line-shapefile-2019-series-information-for-the-primary-and-secondary-roads-state-based-sh. Last accessed on 8th August 2023.

CHAPTER 4 : QUANTIFYING THE ENVIRONMENTAL IMPACTS OF PROPOSED BIOCHAR PRODUCTION FACILITIES USING FOREST BIOMASS IN MICHIGAN

Abstract

Biochar is a carbon-rich product produced through biomass pyrolysis which has great carbon sequestration abilities and is known for amending soils in agriculture. We investigated if Whether biochar can be a viable climate solution in Michigan requires investigation into its production and application. In this regard, a cradle-to-grave life cycle assessment (LCA) has been adopted to quantify the environmental impacts of stationary and portable biochar production units. The LCA encompassed the cultivation of biomass feedstock, hauling, conversion by pyrolysis, biochar hauling, and application to agricultural land. The functional unit (FU) of the study is per the state of Michigan and is expressed per tonne of dry feedstock used, due to different reference flows for stationary and portable units. Stationary units have a net GWP of -14.78 tonne CO2e/FU while it was -14.37 tonne CO_2e/FU for portable units, where aboveground and belowground carbon sequestered during cultivation are primary contributors in making the system's carbon negative. Portable units are able to sequester 1.88 times more carbon than stationary units while growing the feedstock; the figures are -77.24 tonne CO_2e/tonne BC and -42.24 tonne CO_2e/tonne BC, respectively. The most energy and fuel-intensive processes are field activities during cultivation, followed by harvesting and drying the feedstock. However, despite having procured more biomass for biochar production, portable units are able to fulfill only 57% of the potential biochar demand because of lower conversion yield, 18.6% vs. 35% for stationary units. Further, there is a higher potential biochar demand for the same optimized cost. In contrast, stationary units are able to produce a 15% surplus of biochar than the estimated biochar demand. Around 2.445 tonnes CO_2e/tonne of biochar produced can be sequestered when 10 tonnes of biochar is applied per acre over a 30-year rotation for both stationary and portable facilities. Study outcomes bridge the information gap about biochar’s environmental impacts in Michigan through stationary and portable facilities. De-risking forest biomass-to-biochar commercialization will help stakeholders decide whether to establish new biochar facilities in Michigan and across the Great Lakes region.

Keywords: global warming potential, lifecycle assessment, portable units, soil amendment, stationary facilities

4.1 BACKGROUND

Rising temperatures due to global warming have negatively impacted the natural environment and its inhabitants over the past few decades. From 2001-2020, a total of 373,930 acres burned due to wildfires in the US. The total number of fires was 7273, burning an average of 62.63 acres per fire (National Centers for Environmental Information, 2023). The fire intensity determines the damage caused to wildlife, forests, and the affected ecosystems. Thick and flammable vegetation from forest floors is cleared out when low-intensity fires burn at ground level, while high-severity fires remove tree canopies and scorch soil and tree roots (Meghan Snow, 2022). There are also adverse effects on air quality and health, accounting for around 4,000 premature deaths and an economic loss of $36 billion annually in the US (Pan et al., 2023). In 2021 Michigan reported 2,379 acres of land burned due to wildfire (Department of Natural Resources, 2021). Firefighters respond to 10,000-12,000 wildfires in the state annually, with most of them occurring in spring under dry and windy conditions (MI DNR, 2023). Global warming causes the debris and dead vegetation left on the ground to keep getting drier and hotter, essentially becoming fuel for causing wildfires.

The Billion Ton report suggests leaving 30% of logging residues on the ground to maintain ecological balance (soil protection, animal habitat) and soil carbon (Langholtz et al., 2016). Michigan Woody Biomass Harvesting Guidance suggests leaving 17% - 33% of residues on harvested sites in forests to maintain the ecological balance and protect soil and habitat; Michigan's woody residues were estimated to be 8.03 million dry tonnes in 2017 (Gc et al., 2017). Approximately one unit of non-merchantable slash/logging residue is produced for every four units of merchantable forest products (B. Cook, 2017). Collecting, transporting, handling, and utilizing these non-merchantable logging residues poses economic challenges in addition to the environmental risks of being fuel for wildfires if left unattended.

Biochar has been proposed to mitigate the economic and environmental challenges that untreated non-merchantable biomass brings with them. Biochar is a carbon-rich product produced through pyrolysis where biomass/fuel is thermally decomposed in the absence/limited supply of oxygen. Applications of biochar range from heat and power production, metallurgical applications, agriculture, and animal husbandry to medical use (Weber & Quicker, 2018). It is also commonly known as char when used as a soil amendment in agriculture and helps in improving soil health (Qian et al., 2015) through increasing water holding capacity, soil organic carbon, and cation exchange capacity (Kamali et al., 2022a). Producing biochar and burying it in soil (application as soil amendment) has the ability to remove carbon dioxide directly from the atmosphere through the uptake of plants (Glaser et al., 2009). Biochar can retain carbon in soils for thousands of years and has been shown to decrease carbon footprint when it is land applied, it is difficult to draw a general conclusion as all the mechanisms are not fully understood yet and data availability is only site and parameter specific (Nair & Mukherjee, 2022).

Biochar can be produced at different scales depending on the socioeconomic conditions involved, helping systems achieve economies of scale and operating costs (Brassard et al., 2019). The first chapter of this thesis quantified the potential supply of biomass and potential demand for biochar by optimizing transportation costs when stationary and move & park mobile units are used. Stationary facilities have been considered to be large-scale units, fixed at one location while move & park mobile facilities are small-scale units that relocate every three months between four locations throughout the year. Although biochar has high carbon sequestration abilities, the use of fossil fuels in every stage of the production process from cultivation of biomass to conversion and land application of biochar cannot be denied. To understand the environmental impacts of such biochar systems, this study conducts a life-cycle assessment (LCA) and quantifies the effects using the metric of global warming potential (GWP). Since Michigan currently does not produce biochar commercially, the novelty of this study lies in quantifying the environmental impacts of biochar production using biomass if new facilities were established in optimal locations.

An LCA is a methodology to evaluate the environmental impacts caused by the manufacturing till the end-of-life use of a product (Muralikrishna & Manickam, 2017) while GWP measures the amount of energy required to absorb one ton of gas over a certain period of time, relative to the emissions of one ton of CO_2 (Booth, 2023). The four stages involved under ISO 14040 guidelines for conducting an LCA are goal and scope definition, inventory analysis, impact assessment, and interpretation. This LCA encompassed cultivation; biomass procurement; transportation; drying; biochar production; transportation of biochar: and biochar application to agricultural land. However, it is important to note that the lack of availability of relevant data, time, resources, and finances affects the quality of results an LCA can provide (Curran, 2006).

Slow pyrolysis uses a temperature between 300°C and 700°C and primarily produces biochar with a conversion yield of 35% (Brown et al., 2011a). On the contrary, fast pyrolysis takes place between 500°C – 1000°C and produces only 12% of biochar, with bio-oil being the primary product in the process (75%) (Pagliuso, 2010). The stationary facilities considered in this study resemble large commercial reactors with conversion yields of 35% while the move & park mobile facilities considered here account for the average conversion yield of existing mobile pyrolytic units at approximately 20%. Biochar could offset 9% of Europe emissions per year (Glaser et al., 2009) and up to 4.5% of annual national carbon emissions in China, sequestering approximately 920 kgCO_2e per ton of crop residues used as feedstock (Yang et al., 2021). An LCA conducted in Chile concluded that one ton of biochar produced at 500 C (slow pyrolysis) is able to sequester up to 2.74 CO_2e of greenhouse gas emissions when forest residues were used as feedstock and biochar was land applied as a soil amendment (Muñoz et al., 2017).

Increased fuel loads (woody biomass) in the forests along with long and dry climatic conditions have caused forest fires to be extreme and recurrent in the US (P. Cook & Becker, 2017). An overload of stands and small-diameter trees in the forests due to the suppression of fire activities increases fuel loads (Noss et al., 2006). A 50% increase in fire occurrences in the western US by the mid-21st century has been predicted (Liu et al., 2014). High temperatures and oxygen availability during this wildfire produce gases along with pyrogenic carbon (PyC), a chemically stable form of carbon (DeLuca et al., 2020). Wildfire charcoal is a form of PyC that is produced naturally during forest and vegetation fires, burning 300-460 Mha (4% vegetated land surface) globally every year (Santín et al., 2017).These vegetation fires are deemed as a significant global carbon sink and produced 116–385 Tg of pyrogenic carbon each year. (Santín et al., 2017) also draws attention to another form of PyC which is caused anthropogenically, known as biochar. Unlike wildfire charcoal, biochar is a product of pyrolysis where biomass goes through incomplete combustion under controlled temperatures. Biochar is produced through the pyrolysis of biomass (pyrolysis is a thermochemical conversion conducted in the absence/limited supply of oxygen) (Allohverdi et al., 2021). Since there are no commercial biochar processing facilities in Michigan, there is a big gap in knowledge related to the production technologies, economic and environmental feasibility of biomass to biochar conversion in the state.

Throughout the western United States and Canada, slash pile burning is a common practice after logging operations (Fornwalt & Rhoades, 2011). The practice of pile burning is used to remove any debris from the forest floors and is a preferred choice of land managers (Kalabokidis & Omi, 1998) as it is an effective and efficient way to reduce the risk of future fires (Jang et al., 2017). Incinerating residues on site has been the primary method of dealing with forest residues, which contribute to increasing CO_2 emissions, emit particulate matter, and change soil productivity (Puettmann et al., 2020), including underlying soil and vegetation (Rhoades et al., 2015). The soil type, climate of the location, and methods used for pile burn soil compaction and displacement are impacted (Jang et al., 2017). The removal cost of residual slash after logging operations is lower for pile burns compared to alternatives of air curtain burning or whole tree removal (Mott et al., 2021). However, if biomass left on the forest floors is utilized for biochar production, it can help mitigate climate change along with its use as a soil amendment.

These portable units are able to convert biomass to biochar on-site, in order to reduce the costs and emissions involved in transporting the feedstock (Berry et al., 2018; Sahoo et al., 2019). Compared to slashing piles and burning the forest residues left behind, the portable biochar production systems were able to curb the negative environmental impacts; the GWP was lower by 2.7, 1.92-2.83 and 1.9 tonne CO_2e/tonne fixed carbon for OK, BSI, and ACB compared to pile burn (Puettmann et al., 2020). Although portable small-scale biochar production systems can be an economically viable option, there are not enough studies conducted to compare them with stationary units, especially when biochar is the only product. Most portable systems have been optimized to produce bio-oil as the primary product which can be upgraded for transportation fuel (Mirkouei et al., 2016). Compared to stationary units, portable units were able to reduce the greenhouse gas emissions associated with transporting the feedstock when vineyard residues were used as feedstock for biochar production (Rosas et al., 2015). Portable systems such as Air Curtain Burner (ACB) and Oregon Kiln (OK) require minimal preparation for feedstock before pyrolysis and have been known to have lower negative environmental effects compared to Biochar Solutions Incorporated (BSI) (Puettmann et al., 2020). Up to 1.4 tonnes CO_2e/ tonne of biomass can be mitigated by energy applications and biochar's use as a soil amendment (Field et al., 2013).

Despite the merits of using biochar as a carbon capture and storage technology, it should be noted that every stage in the LCA, from cultivation and harvest to chipping, drying, and transporting are all fossil fuel intensive. The system boundary of the LCA determines the extent of environmental impact caused due to biochar production (Sahoo et al., 2019). Electricity is required to conduct the pyrolysis process itself, regardless of whether the process occurs in stationary or portable units; this electricity is produced using non-renewable and fossil fuels (Kamali et al., 2022a). To conduct the pyrolysis process itself, stationary or portable, electricity is required, which is produced using non-renewable and fossil fuels (Kamali et al., 2022b). Research has been conducted on the economics of biochar production where mobile production units have been proposed to lower the cost of transporting forest residues to facilities (Berry et al., 2018; Sahoo et al., 2019). However, these studies did not investigate the environmental impacts associated with using large-scale (stationary) and small-scale (portable) systems. The lifecycle assessment of portable systems using forest residues as feedstock was conducted by (Puettmann et al., 2020a) but it did not make large-scale (stationary) units.

4.2 MATERIALS & METHODS

The first step of the LCA was to define the goal and scope of the study of an ISO-standardized LCA where the purpose of the study was detailed along with the product being analyzed (Curran, 2016). The factors discussed in this definition stage included the functional unit, impact indicators, and system boundary, including the inputs, outputs, and projected pathways taken to analyze the product's environmental impacts. This study's goal was to identify the annual global warming potential (GWP) when biochar is produced using stationary and portable approaches for biochar production in Michigan. The system boundary started from the cultivation of feedstock and ended with biochar application to agricultural land in Michigan. The study's geographical scope was the State of Michigan for both scenarios. This LCA is an extension of the economic feasibility study conducted by optimizing transportation costs for biomass procurement and biochar production. At the same delivered wood price, the amount of feedstock available for biochar production was different for stationary and portable units, as the reference flows were different for both. Taking the LCA approach to identify the environmental impacts of biomass for biochar production in Michigan is novel, especially because of the comparison between stationary and move & park production technologies. Hence, assumptions were made to best fit the geographic scope of Michigan within a one-year time horizon.

The second step in the LCA was the inventory analysis (LCI) which includes data collection, validation, and impact reporting per functional unit. In this LCA, allocation was avoided (as recommended by international standards) as there is only one product in each scenario analyzed. However, if there were multiple products for different scenarios, the burden of impacts needed to be allocated based on the mass allocation of the flow by weight basis or through economic allocation based on annual average prices over a number of years (Haque, 2020). The State of Michigan was selected as the functional unit (FU) in this study, meaning that environmental impacts for biochar application are reported for the State of Michigan and no neighboring regions. This FU was chosen because both scenarios have different input biomass and output biochar flow rates and because this choice simplifies the comparison of total benefits and burdens between each system to inform better inform stakeholders in Michigan. The functional unit per state of Michigan represented the impact per tonne of biomass used as feedstock for biochar production.

The third step was the impact analysis in the LCA (LCIA) where both quantitative and qualitative environmental impacts were considered to calculate desired effects within the defined goal and scope (Z. Wang & Liu, 2021). The primary task of the LCIA was to quantify the contributions of different system components to environmental impact categories. The impact category in this study was global warming (GW) when biochar is produced using biomass through stationary and portable technologies. GW is used to compare the impact of different greenhouse gases relative to a reference gas (carbon dioxide, CO_2); e.g., the global warming potential, GWP, of CO_2 is 1 g CO_2/g CO_2 (Ohara, 2022).

The fourth and final stage of the LCA identifies, quantifies, verifies, and evaluates the data obtained from the second and third stages (LCI and LCIA) (Cao, 2017). The LCA interpretation phase outlines the study results and provides recommendations, recognizing data quality limitations. Data quality indicators (DQI) were used as per the Weidema method (Weidema & Wesnæs, 1996). DQIs assess the data based on completeness (C), reliability (R), temporal correlation (TC), geographical correlation (GC), and further technological correlation (FTC). The DQIs are scored between 1 and 5, with 1 being the highest score the data can obtain and 5 being the lowest. For example, data with the highest quality would have a DQI of 1, while a 5 would be the lowest.

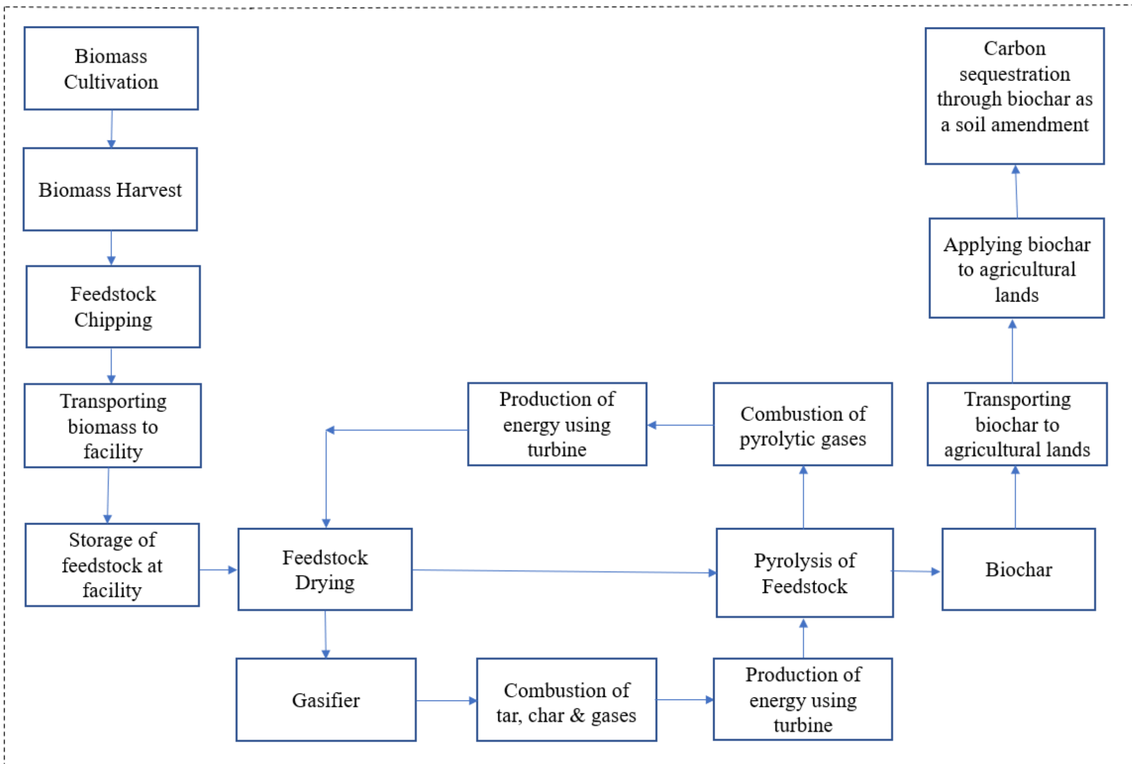

Figure 4.1 System boundary for cradle-to-grave life cycle assessment for biochar production using stationary & portable facilities in Michigan

Cultivation

Logging residues, such as slash, are the feedstock considered for biochar production. Slash consists of small-diameter trees, branches, and treetops that are left behind in the forest after the merchantable wood has been removed. As Michigan grows a large variety of tree species, we selected a more common species to represent all others, namely jack pine. Jack pine is the 17th most common tree in Michigan out of 85-90 species (Michigan State Forestry Extension Team, 2014). Jackpine requires harvest and regrowth to create a Kirtland warbler habitat, and because it tends to become fire-prone. Jackpine's ultimate analysis data was obtained from the (Phyllis 2, 2023) database. Feedstock characteristics are shown in Table 1.

Table 4.1 Feedstock characteristics

Characteristics	Values	Data Quality Indicators				
		R	C	TC	GC	FTC
Feedstock name [a]	Jack Pine waste USA (#880)	1	1	2	2	2
Ultimate analysis [b]	C : 31.34 % ; H : 3.46 % ; O : 23.83 %	1	1	1	1	1

Table 4.1 (cont'd)

Empirical formula (calculated)	$C H_{1.33} O_{0.57}$	1	1	1	1	1
Volume [b]	99.68 m^3/acre	2	2	2	2	2
Density [c]	500 kg/m^3	2	2	2	2	2
Mass (calculated)	49.84 green tonne/acre ; 24.92 dry tonne/acre	1	1	1	1	1
Wood specific gravity [b]	0.43 g/cm^3	1	1	2	2	2
DBH [b]	10 inches ; 25 cm					

a. (Phyllis 2, 2023)
b. (Michigan State Forestry Extension Team, 2014)
c. (The Wood Database, 2023)

The economic feasibility assessment obtained biomass availability at the average delivered wood price in Michigan. The amount of feedstock available for stationary and portable systems varied, and their respective amounts were used as reference flows for the LCA assessment. We calculated the GWP for growing the feedstock based on the biomass procured for each of these production approaches. The field production phase includes seeding and application of pesticides. While the equipment activities include land preparation, transplanting, irrigation, mowing, pruning, stalking, herbicide application, insecticide application, and fertilization. Diesel fuel was used for cultivation, which accounted for 70% of this stage's GWP (Ingram, 2012).

Table 4.2 Life-cycle inventory analysis for growing the feedstock

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
Biomass procured (calculated)	2,409,000 GT	4,098,000 GT	1	1	5	1	1
Number of trees grown [d]	1,976 trees/hectare ;	800 trees/acre	2	1	5	3	3
Land required for cultivation (calculated)	48,329 acres	82,229 acres	1	1	5	1	1
GWP [d]	0.18 tonne CO_2e / FU		2	3	5	3	2
	0.51 tonne CO_2eq/tonne BC	0.96 tonne CO_2eq/tonne BC					

Harvest

Harvesting the feedstock includes digging, removal of culls, loading and unloading the biomass. The loading and unloading time estimated here is 40 minutes in total for a one-way hauling trip.

Table 4.3 Life-cycle inventory analysis for harvesting the feedstock

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
Biomass procured (calculated)	2409,000 GT	4,098,000 GT	1	1	1	1	1
GWP [d]	0.20 tonne CO_2e/FU		2	3	2	3	2
	0.57 tonne CO_2e/BC	1.08 tonne CO_2e/BC					

FU = state of Michigan (i.e., per dry tonne feedstock used for stationary and move & park mobile facilities individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for move & park units = 18.6%)
d.Calculated using references values from (Ingram, 2012)

Aboveground & belowground carbon

The aboveground (ABG) includes branches, bark, stems, and foliage and can be measured by either destructive or non-destructive sampling techniques (Habib & Al-Ghamdi, 2021). Belowground biomass (BGB) includes the roots and rhizomes where carbon is stored after decay and mineralization (Craft, 2013). The AGB and BGB are used to calculate the carbon stored in the trees during cultivation. The AGB carbon content varies by species but is usually within the 45-50 wt.% (Burt et al., 2021). Equations 1 and 2 were used to calculate the ABG and BGB, respectively, and carbon stock was assumed to be 50% of the calculated values (de la Cruz-Amo et al., 2020). We multiplied the carbon stock in AGB and BGB with 3.67 to determine the GWP equivalent (i.e., conversion of C to CO_2).

$$AGB = 0.0673 * (\rho * DBH^2 * H)^{0.976} \text{ (Chave et al., 2014)} \quad 1$$

$$BGB = 0.285 * (DBH)^{1.993} \text{ (Chave et al., 2005; Kachamba et al., 2016)} \quad 2$$

AGB = aboveground biomass; BGB = belowground biomass; ρ = wood specific gravity = 0.43 g/cm³ ; DBH = 25 cm

Table 4.4 Life-cycle inventory analysis for aboveground and belowground carbon

Characteristics	Values		Data Quality Indicators				
	Stationary	Portable	R	C	TC	GC	FTC
Aboveground biomass	5,884,000 tonnes	10,011,000 tonnes	2	3	3	4	3
Amount of C in ABG	2,942,000 tonnes	5,005,000 tonnes	2	3	3	4	3
GWP for C stock in aboveground biomass	-8.965 tonne CO_2e/FU		2	3	3	4	3
	-25.61 tonne CO_2e/BC	-48.20 tonne CO_2e/BC	2	3	3	4	3
Belowground biomass	3,516,000 tonnes	5,982,000 tonnes	2	3	3	4	3
Amount of C in BGB	1,758,000 tonnes	2,991,000 tonnes	2	3	3	4	3
GWP for C stock in belowground biomass	-5.357 tonne CO_2e/FU		2	3	3	4	3
	-15.31 tonne CO_2e/BC	-28.80 tonne CO_2e/BC	2	3	3	4	3

FU = State of Michigan (i.e., per dry tonne feedstock used for stationary and portable systems individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for portable units = 18.6%)
**Values are calculated and rounded off to the closest integer*

Chipping

Jack pine's density affects the hourly biomass chipping rate and the rate of fuel consumption (Spinelli & Magagnotti, 2014). A chipping loss of 0.5% of biomass was assumed while diesel fuel was consumed to run the chipping operations before hauling the biomass to the respective facilities; 1 liter of diesel produced 2.676 kg CO_2e.

Table 4.5 Life-cycle inventory analysis for chipping the feedstock

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
Amount of biomass chipped	2,409,000 GT	4,098,000 GT	1	1	1	1	1
Average operating hours annually	1,500 hours		2	2	4	5	4

Table 4.5 (cont'd)

Average input biomass capacity	120 m^3/hour		2	2	4	5	4
Density of jack pine	500 kg/m^3		1	1	4	2	3
Annual input capacity (calculated)	18,000 m^3		2	2	4	5	4
Fuel consumption	0.5 liter/m^3		2	2	4	5	4
GWP	0.0054 tonne CO_2e/FU		2	2	4	5	4
	0.0154 tonne CO_2e/BC	0.0288 tonne CO_2e/BC					

FU = State of Michigan (i.e., per dry tonne feedstock used for stationary and portable systems individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for portable units = 18.6%)
**Values are calculated and rounded off to the closest integer ; GT = green tonnes*

Transporting feedstock to the facility

Biomass density was used to determine the amount truck can haul, considering weight and volume limitations. At the average delivered wood cost for biomass in Michigan, the corresponding distance traveled is 67.5 miles and we calculated the GW for transporting biomass to facilities within this distance. To determine the GW for trucking, distance, and mass hauled were converted into ton-miles and multiplied by the emissions factor of 161.8 g CO_2eq/ton-miles (Mathers, 2015). By determining the amount of biomass one truck can haul, we also calculated the total number of trucks required to transport all biomass to the respective facilities.

Table 4.6 Life-cycle inventory analysis for transporting biomass to facility

Characteristics	Values Stationary	Move & Park	Data Quality Indicators R	C	TC	GC	FTC
Average density of biomass	500 kg/m^3		1	1	2	2	2
Truck capacity for transporting biomass*	74m^3		2	2	2	2	2
Mass of biochar that 1 truck can transport (calculated)*	37 tonnes		1	1	1	1	1
Amount of biochar transported to agricultural lands*	2,397,000 GT	4,098,000 GT	1	1	1	1	1
Number of one-way haul trucks required to transport biomass*	64,630	110,518	1	1	2	2	2

Table 4.6 (cont'd)

GWP	0.00420 tonne CO_2e/FU	0.00224 tonne CO_2e/FU	1	1	2	2	2
	0.1204 tonne CO_2e/BC		1	1	2	2	2

FU = State of Michigan (i.e., per dry tonne feedstock used for stationary and portable systems individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for portable units = 18.6%)
GT=green tonnes
**Values are calculated and rounded off to the closest integer*

Drying the feedstock

Biomass feedstock was assumed to have 50 wt.% moisture content. Prior research suggests that the optimal moisture contents range from 6-12 wt.% prior to thermal conversion (Filbakk et al., 2011; Huang et al., 2017; Obernberger & Thek, 2004; Stelte et al., 2011). Reducing the moisture content for stationary facilities was performed by a rotary drum dryer (Sokhansanj & Webb, 2016). For portable units, the biomass moisture content was reduced using a belt dryer (Eggink et al., 2018). A mass loss of 3 wt.% was assumed during storage. The portable unit's dryer operates for 3,600 hours annually, while the stationary unit's rotary drum operates for 5,760 hours annually (Sokhansanj & Webb, 2016). The dryer efficiency was assumed to be 83% for both scenarios (Eggink et al., 2018). The energy required to remove 50% of the moisture was calculated using the latent enthalpy of vaporization for water (2,256 kJ/kg at 100°C and 101.3 kPa) in addition to the energy required for raising the temperature of biomass for the drying process (Energy=Mass*Cp*Change in Temperature). The Cp (constant pressure specific heat) for the biomass (pine) considered here is 1.38 kJ/kg K. The gases produced during the pyrolysis are recycled and combusted to produce energy for running the dryer for both systems. The GW for the additional dryer energy is found by determining the fuel required and converting the emissions into CO_2 equivalents (CO_2eq). 1 liter of diesel produces 2.676 kgCO_2eq.

Table 4.7 Life-cycle inventory analysis for drying the feedstock

Characteristics	Values Stationary	Move & Park	Data Quality Indicators R	C	TC	GC	FTC
Amount of biomass at 50% MC	2,397,000 GT	4,098,000 GT	2	3	3	3	3
Amount of biomass after storage losses	2,325,000 GT	3,975,000 GT	2	3	3	3	3
Amount of biomass after drying	1,162,500 DT	1,987,500 DT	2	3	3	3	3
Feed-in capacity	2000 kg/hour	523 kg/hour	2	3	3	3	3
GWP	0.0135 tonne CO_2e/FU 0.038 tonne CO_2e/BC	0.0193 tonne CO_2e/FU 0.125 tonne CO_2e/BC	2	3	3	3	3

FU = state of Michigan (i.e., per dry tonne feedstock used for stationary and portable systems individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for portable units = 18.6%)
**Values are rounded off to the closest integer*

Pyrolysis

Pyrolysis is the thermal decomposition of biomass in an oxygen-deprived environment (Davies et al., 2020), where the feedstock and conversion temperature determine the yield from biomass to biochar conversion. The ideal technology to produce biochar is through slow pyrolysis which can take place between 300°C-700°C; biochar produced at 500°C through slow pyrolysis produced biochar with a carbon content of 79% and had a conversion yield of 27% (Y. Lee et al., 2013). Biochar conversion yields varied between 25%-50% for large-scale commercial reactors, where the most widely used yield through slow pyrolysis is 35% (El-Naggar et al., 2019). Unlike slow pyrolysis, biochar is the by-product when fast pyrolysis is used as the conversion technology, with bio-oil being the primary product. The biochar yields are between 12%-15% (Mašek, 2016), and 10%-20% (Chun et al., 2021). Often, the gases produced during the conversion processes are combusted to heat the reactor (Pelaez-Samaniego et al., 2022) or run other machines such as the dryer.

To determine the conversion yields for move & park units, we examined different existing mobile pyrolytic units, such as the Oregon Kiln (OK), Air Curtain Burner (ACB), and

Biochar Solutions Incorporated (BSI). The conversion yields reported for these portable systems range between 13%-20% (Eggink et al., 2018; Puettmann et al., 2020a) and 4%-10% (Delaney & Miles, 2019). In this study, we considered stationary units to be large, commercialized biochar production facilities and move & park mobile units to be small-scale and portable. We considered conversion yields of 35% (Mohan et al., 2014) for stationary units following the slow pyrolysis production technology and 18.6% (average of the biochar conversion yields calculated from the literature review) for portable processing units.

We determined the reactions involved in the biomass-to-biochar conversion (Tables 8, 9, 10, 11). We determined the specific capacity of heat for tar and char obtained during gasification reactions (Equations 12 and 13, (Popescu et al., 2020)). The empirical formula for tar was $CH_{1.25}O_{0.34}$ where the HHV was 26.1 MJ/kg (Trubetskaya et al., 2021). For char, we obtained calculated the empirical formula to be $CH_{0.45}O_{0.10}$ with an HHV of 31.11 MJ/kg (Phyllis 2, 2023). Energy balances were performed to identify the heat produced by combusting the tar, char and gases produced during the pyrolysis and gasification reactions for both these systems. The gases produced through pyrolysis were combusted to produce energy which was used to run dryer operations. On the other hand, 5.61% of the procured biomass for each of these systems was used to run the gasifier to produce energy for the pyrolysis reactor. A turbine efficiency of 90% was assumed for the calculations.

Table 4.8 Mass and molar balances for pyrolysis and combustion of produced gases during biomass to biochar conversion

Stationary Units	
Stoichiometric equation for pyrolysis (percentage basis, conversion yield = 35%): $CH_{1.33}O_{0.57} + 0.115\ H_2O \rightarrow 0.35\ CH_{0.45}O_{0.10} + 0.65\ CO + 0.70125\ H_2$	3
Stoichiometric equation for pyrolysis (molar basis, conversion yield = 35%): $CH_{1.33}O_{0.57} \rightarrow 0.56\ CH_{0.45}O_{0.10} + 0.44\ CO + 0.465\ H_2 + 0.0.074\ H_2O$	4
Table 4.8 (cont'd)	
Stoichiometric equation for combusting gases produced during pyrolysis (molar basis): $0.44\ CO + 0.465\ H_2 + 0.0.074\ H_2O + 0.4525\ O_2 + 1.7014\ N_2 \rightarrow 0.44\ CO_2 + 0.539\ H_2O + 1.7014\ N_2$	5

Portable units	
Stoichiometric equation for pyrolysis (percentage basis, conversion yield = 18.6%): $CH_{1.33}O_{0.57} + 0.2626\ H_2O \rightarrow 0.186\ CH_{0.45}O_{0.10} + 0.814\ CO + 0.88575\ H_2$	6
	7

Table 4.8 (cont'd)

Stoichiometric equation for pyrolysis (molar basis, conversion yield = 18.6%):
$CH_{1.33}O_{0.57} + 0.16\ H_2O \rightarrow 0.30\ CH_{0.45}O_{0.10} + 0.70\ CO + 0.7575\ H_2$

Stoichiometric equation for combusting gases produced during pyrolysis (molar basis): 8

$0.70\ CO + 0.7575\ H_2 + 0.72875\ O_2 + 2.7401\ N_2 \rightarrow 0.70\ CO_2 + 0.7575\ H_2O + 2.7401\ N_2$

Table 4.9 Mass and molar balance of gasification and combustion of tar, char, and gases

Stoichiometric equation for gasification (percentage basis, tar =15%, char =5%): 9
$CH_{1.33}O_{0.57} + 0.286\ H_2O \rightarrow 0.05\ CH_{0.45}O_{0.10} + 0.15\ CH_{1.25}O_{0.34} + 0.80\ CO + 0.846\ H_2$

Stoichiometric equation for gasification (molar basis): 10
$CH_{1.33}O_{0.57} + 0.1996\ H_2O \rightarrow 0.08\ CH_{0.45}O_{0.10} + 0.24\ CH_{1.25}O_{0.34} + 0.68\ CO + 0.6966\ H_2$

Stoichiometric equation for combusting gases tar, char and gases produced during gasification (molar basis): 11
$0.08\ CH_{0.45}O_{0.10} + 0.24\ CH_{1.25}O_{0.34} + 0.68\ CO + 0.6966\ H_2 + 1.0475\ O_2 + 3.9386\ N_2 \rightarrow 1\ CO_2 + 0.8646\ H_2O + 3.9386\ N_2$

Molar mass of tar ($CH_{1.25}O_{0.34}$)=18.69g; Molar mass of char ($CH_{0.45}O_{0.10}$)=14.05g; 1 mol of O_2 produces 3.76 mols of N_2

Table 4.10 Equations for calculating specific heat capacities for tar and char

Specific capacity of heat for tar :

$Cp = (-2.093 * 10^5 * T^{-2.2}) + 1.825$ 12
$Cp = 3.3*10^{-5}$ kJ/mol K (Stationary), $Cp = 2.62*10^{-5}$ kJ/mol K (portable)

Specific capacity of heat for char :

$Cp = 0.45 + (0.00194*T) - (5*10^{-7}*T^2)$ 13
$Cp = 2.56*10^{-5}$ kJ/mol K (stationary); $Cp = 3.31*10^{-5}$ kJ/mol K (portable),

Table 4.11 Life-cycle inventory analysis for pyrolysis

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
GWP	0.0041 tonne CO_2e/FU	0.0047 tonne CO_2e/FU	3	3	3	4	4
	0.012 tonne CO_2e/BC	0.025 tonne CO_2e/BC	3	3	3	4	4

FU = state of Michigan (i.e., per dry tonne feedstock used for stationary and move & park mobile facilities individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for move & park units = 18.6%)
**Values are rounded off to the closest integer*

Transporting biochar to cropland

The cropland area where biochar could be land applied was calculated from the economic feasibility study conducted prior to the LCA. At the average delivered wood cost for biomass in Michigan, the application areas for biochar were calculated. The corresponding distance traveled at this cost is 67.5 miles (calculated using the methodology in Chapter 1 for baseline delivered wood cost of $25.54/green tonne biomass and biochar transportation cost of $16.66/tonne BC) and we calculated the GWP for transporting biochar to agricultural land within this distance. We considered a 5% loss in transporting, handling, spreading, and loading the biochar from the respective facilities to the agricultural lands. The typical values for biochar bulk densities are in the range of 80kg/m^3-120 kg/m^3 (Brewer & Levine, 2015); the bulk density of biochar produced from forest residues was considered to be 106 kg/m^3 with a truck capacity of 98 m^3 (Bergman et al., 2022).

Table 4.12 Life-cycle inventory analysis for transporting biochar to agricultural lands

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
Average bulk density of biochar	106 kg/m^3		1	1	2	2	2
Truck capacity for transporting biochar	98m^3		2	2	2	2	2
Mass of biochar that 1 truck can transport (calculated)	10.39 tonnes		1	1	1	1	1
Amount of biochar transported to agricultural lands*	386,000 tonnes	349,000 tonnes	1	1	1	1	1

Table 4.12 (cont'd)

Number of one-way haul trips required to transport biochar*	37188	33640	1	1	2	2	2
GWP	0.00420 tonne CO_2e/FU	0.00224 tonne CO_2e/FU	1	1	2	2	2
	0.1204 tonne CO_2e/BC		1	1	2	2	2

FU = state of Michigan (i.e., per dry tonne feedstock used for stationary and move & park mobile facilities individually
BC = amount of biochar produced (yield for stationary units = 35% ; yield for move & park units = 18.6%)
**Values are rounded off to the closest integer*

Applying biochar to cropland

For biochar application to agricultural lands, broadcasting and incorporating the biochar into the soil is suggested (Leppäkoski et al., 2021). Broadcasting is a method of scattering or spreading seeds on the surface of the soil. For small-scale applications, hand broadcasting is recommended while lime/manure spreaders and broadcast seeders are encouraged for large scale applications (Major et al., 2010; Steiner et al., 2007). Plowing methods are suggested to incorporate biochar into the soil and can be achieved through hand hoes, animal draft plows, disc harrows, chisels, or rotary hoes (Major, 2010). However, the use of moldboard plowing is not recommended as it is less efficient in mixing the biochar into the soil and might cause deep biochar layers instead of proper incorporation with soil layers (Blackwell et al., 2009). We prioritized reducing wind losses during the application process and chose to use a manure spreader with moistened biochar and a power harrowing method for plowing (Leppäkoski et al., 2021). Power harrowing is used for tillage, both primary and secondary, and has the capacity to cut and mix the topsoil around seven times more than a moldboard plow (Celik & Altikat, 2022). It can also reduce the negative effects of residue accumulation and soil compaction.

Table 4.13 Life-cycle inventory analysis for applying biochar to croplands

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
Amount of biochar applied to soil*	386,000 tonnes	349,000 tonnes	1	1	1	1	2
Fuel consumption for a manure spreader*	14 liter/hectare ; 35 liter/acre		2	2	2	3	3

Table 4.13 (cont'd)

Fuel consumption for power harrowing	6 liter/hectare ; 15 liter/acre		2	2	2	3	3
GWP	0.0046 tonne CO_2e/FU	0.0025 tonne CO_2e/FU	2	2	2	3	3
	0.0132 tonne CO_2e/BC		2	2	2	3	3

Carbon sequestration through biochar application

The application rate of biochar varies depending on the type of soil and crops to be grown. In one study, it was recommended to apply 22 tonne/hectare (~ 9 tonnes/acre) biochar when growing wheat biomass (Bista et al., 2019) while in another study, the range was between 10–20 tonne/hectare (~ 4-8 tonne/acre) (Gao et al., 2021). The fraction of soil organic carbon that has the fastest turnover time is known as labile carbon, where its oxidation drives the CO_2 flux between the soil and the atmosphere (Zou et al., 2005). In contrast, recalcitrant carbon is the larger fraction of soil organic matter with a slower turnover rate and determines the long-term carbon sequestration potential in soils (McLauchlan & Hobbie, 2004). The reported values for recalcitrant carbon vary depending on the soil type; the estimated values were: 70 -75% (S. et al., 2021); 86% (Belay-Tedla et al., 2009); 98.9 - 99.6% (Lopes de Gerenyu et al., 2008). For this study, we assumed that 86% (an average of the values obtained in literature) of the carbon applied to cropland through biochar will remain in the soil and estimated the biochar application rate to be 10 tonnes/acre.

Table 4.14 Life-cycle inventory analysis for carbon sequestration due to biochar's use as a soil amendment

Characteristics	Values		Data Quality Indicators				
	Stationary	Move & Park	R	C	TC	GC	FTC
Biochar application rate	10 tonnes/acre		2	1	3	3	3
Carbon content in biochar ($CH_{0.45}O_{0.10}$)	85.41%		1	1	2	2	3
Amount of biochar applied*	386,000 tonnes	349,000 tonnes	2	2	2	2	2
Amount of carbon that remains in the soil*	264,000 tonnes	239,000 tonnes	2	2	2	2	2

Table 4.14 (cont'd)

GWP	- 0.856 tonne CO_2e/FU	- 0.455 tonne CO_2e/FU	2	2	2	2	2
	-2.445 tonne CO_2e/BC		2	2	2	2	2

4.3 RESULTS & DISCUSSION

GWP for stationary and portable units per functional unit

Land application biochar is a method for carbon capture and storage. Biochar can improve soil quality and food production capacity (Shukla et al., 2022). The GWP of biochar produced from forest residues is 0.11, 0.25-0.31, and 0.16 tonne CO_2e/tonne of fixed carbon for OK, BSI, and ACB, respectively (Puettmann et al., 2020a). In this study, the net GWP for stationary units is -14.78 tonne CO_2eq/State of Michigan, while it is -14.37 tonne CO_2eq/State of Michigan for portable units (Figure 4.2); per state of Michigan = FU. The difference in the net GWPs is 0.411 tonne CO_2e/FU where the GWP for stationary units is 1.03 times lower compared to portable units.

Both these systems are able to sequester more carbon than the emissions involved in all stages starting from cultivation to the application of biochar to cropland. The GWPs for aboveground and belowground carbon are -8.94 tonne CO_2eq/FU and -5.36 tonne CO_2eq/FU for both stationary and portable units, noting that aboveground carbon is 1.67 times higher than belowground carbon. The amount of carbon sequestered during cultivation is the primary contributor in making the GWPs negative for both these production systems. After biomass is converted to biochar and applied to cropland, we assumed that 80% of carbon from the biochar will remain in the soil. The GWP was -0.466 tonne CO_2eq/FU for portable units and -0.878 tonne CO_2e/FU for stationary units; 1.88 times more carbon can be stored in soil by stationary units due to a higher amount of biochar being produced and applied to agricultural lands.

Harvesting the feedstock has contributed to the highest positive GWP amongst all the stages (except for the carbon sequestered through biochar application in addition to that in aboveground and belowground biomass while growing the feedstock) (Figure 4.3). Although a different amount of biomass was procured through stationary and portable systems, the GWP contribution for the State of Michigan was the same at 0.201 tonne CO_2e. Growing the feedstock contributed to 0.179 tonnes CO_2e/FU and was 1.12 times lower than harvesting. The figures for chipping were 0.0054 tonne CO_2e/FU for both of these systems. Both harvesting, growing the feedstock, and chipping were pre-biomass to biochar conversion stages and contributed to the same GWP when calculated based on the respective amounts of biomass they procured at the optimized transportation cost. Drying contributed to 0.0135 tonne CO_2e /FU and 0.0193 tonne CO_2e/FU for stationary and portable units, respectively. for portable units is higher by 1.43 times compared to stationary units. Research shows that GWP for drying biomass is around 0.0092 tonne CO_2e/FU when wood waste is used as fuel on a moving belt dryer (Haque & Somerville, 2013). The feed-in capacity of the dryer for stationary units is higher than portable units with more operating hours annually, whereas the latter has more procured biomass to process before pyrolysis. More dryer units are required for portable units to dry more biomass and contributing to a higher GWP in comparison. The same trend was observed for pyrolysis where portable units had to process a higher amount of biomass leading to a higher GWP of 0.0048 tonne CO_2e/FU compared to 0.0041 tonne CO_2e/FU for stationary units (lower by 0.85 times). The GWP for stationary units was higher when biochar was applied to cropland at 0.0046 tonne CO_2e/FU (higher by 1.88 times compared to portable units). This is due to a higher amount of biochar being produced for stationary units (higher conversion yield of 35 wt%), transported, and applied to croplands.

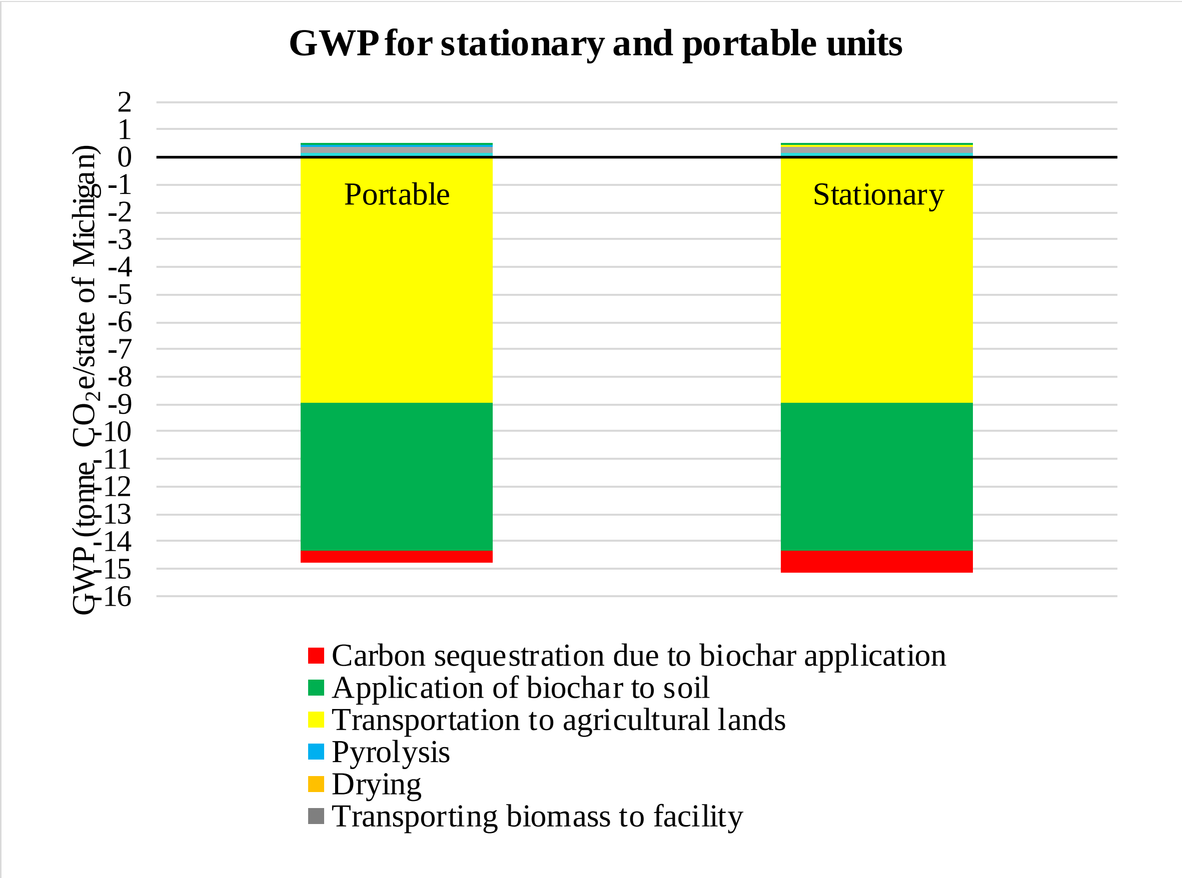

Figure 4.2 Global warming potential (GWP) for portable and stationary units per state of Michigan

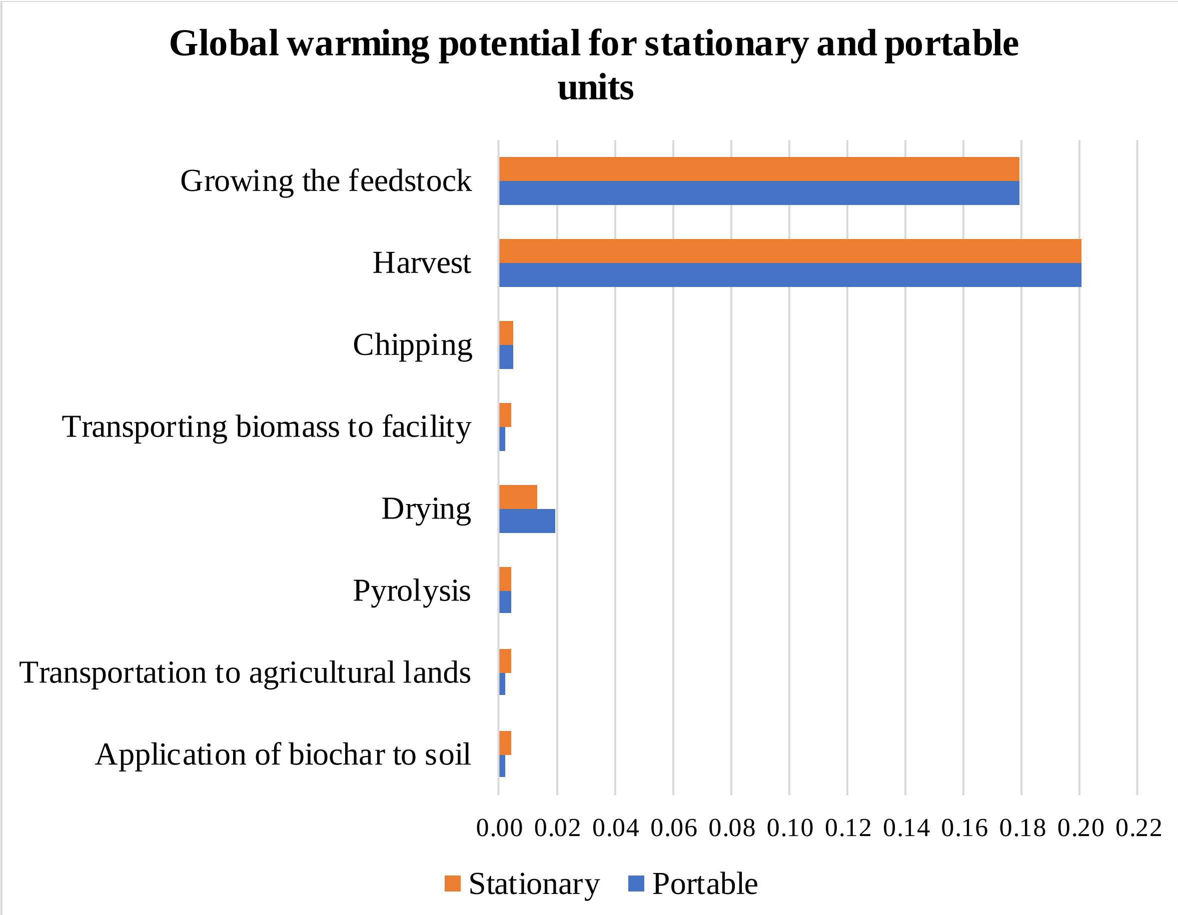

Figure 4.3 Contribution analysis of LCA production stages in net global warming potential (GWP)

Sensitivity analysis of varying biochar yields for stationary and portable units

For stationary units, +100% corresponded to a biomass to biochar conversion yield of 70% and -100% corresponded to 0.35% (Figure 4). For portable units, 37.2% conversion yield corresponded to +100% while it was 0.186% for -100% on the sensitivity analysis scale (Figure 5).The sensitivity analysis of GWP per tonne biochar (per tonne BC) produced for stationary facilities and portable facilities demonstrates that harvesting is impacted the most when the biochar yield is varied, followed by growing the feedstock. However, GWP figures for portable units are higher compared to stationary units for all the categories. With changing biochar yields, the GWP for all stages increase except for aboveground carbon, belowground carbon and carbon sequestered through biochar application, demonstrated through the secondary axis. Aboveground biomass is the most sensitive with changing biochar yields for both the systems followed by belowground carbon and carbon sequestered through biochar application. For all stages, portable units have a higher GWP compared to stationary units when biochar yield is varied from -100% to +100%, 0% being the base case scenario. Stages of chipping, transporting biomass to facilities, pyrolysis, transporting biochar to cropland and applying biochar to land were the least impacted due to varying biochar yields for both these systems. The amount of carbon sequestered through stationary units was more sensitive to biochar yield compared to that for portable units; the corresponding GWP range was smaller for portable units. An opposite observation was made for drying and its sensitivity towards biochar yield, where stationary units had a smaller corresponding GWP range when biochar yield is varied.

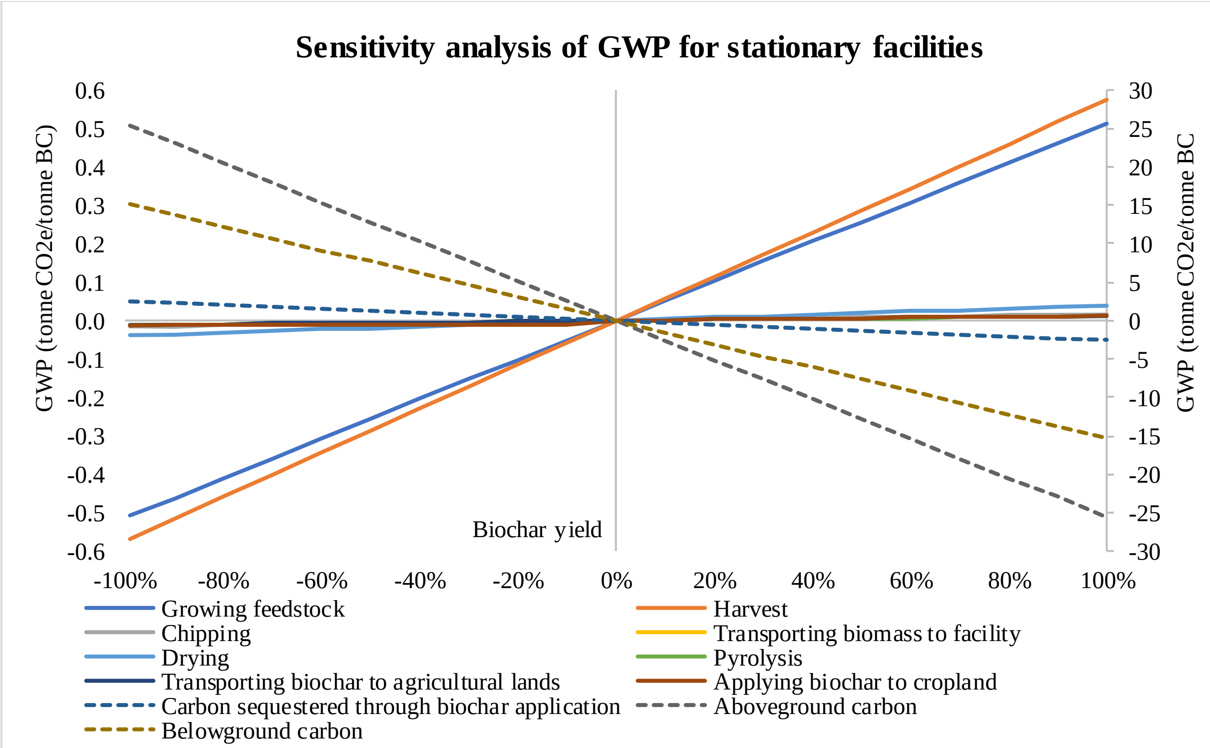

Figure 4.4 Sensitivity analysis of GWP for stationary units due to varying biochar yields (the dotted lines correspond to the represent the data on the secondary axis)

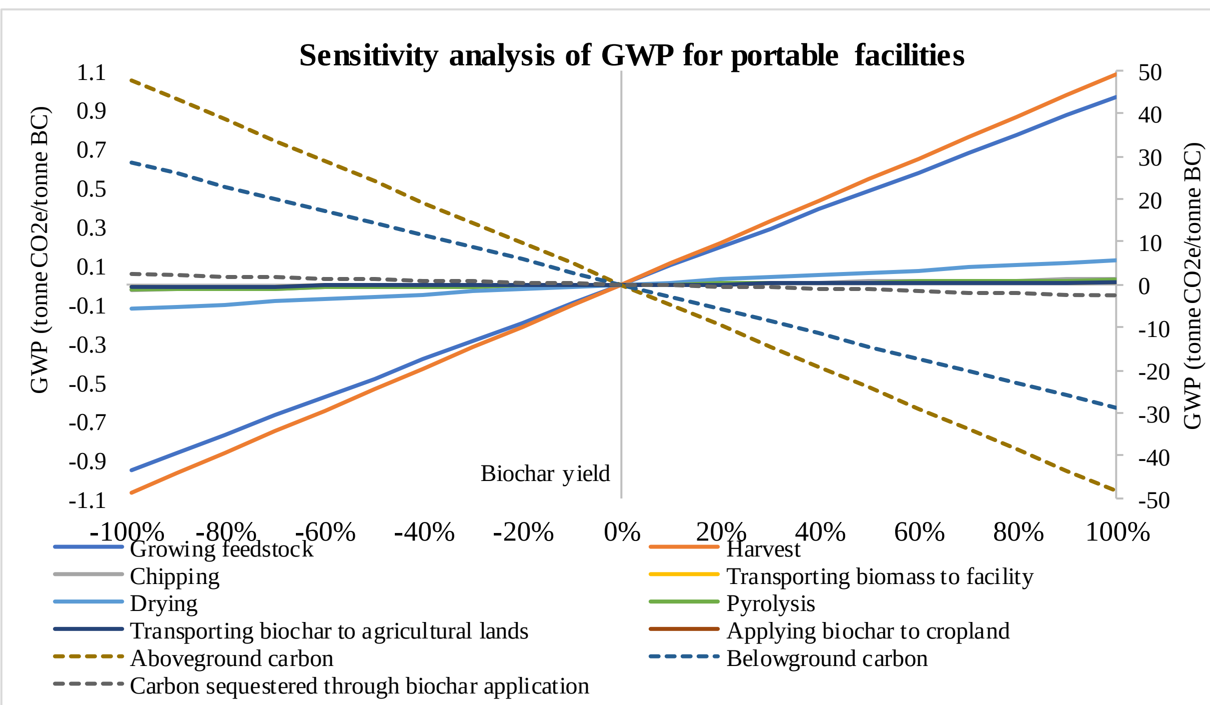

Figure 4.5 Sensitivity analysis of GWP for Portable units due to varying biochar yields (the dotted lines correspond to the data on the secondary axis)

GWP per tonne of biochar produced for stationary and portable facilities in Michigan

The net GWP obtained for stationary units is -42.24 tonne CO_2e/ tonne BC while it was higher by 1.83 for portable units at -77.24 tonne CO_2e/ tonne BC (Table 15). portable units are able to sequester a higher amount of carbon and are a more environmentally friendly method of producing biochar. However, the primary reason for them having a lower GWP than stationary units is due to the carbon sequestered during growing the feedstock. portable units relocate annually (every three months) and are able to procure a 4.1 million green tonnes of biomass at the baseline cost (2.05 million dry tonnes); it is higher by 1.71 times compared to stationary units that are able to procure 2.4 million green tonnes (1.2 million dry tonnes). During the cradle to grave life cycle assessment, the cultivation stage included the amount of carbon stored in the aboveground and belowground biomass. Having a higher amount of feedstock to produce biochar (portable units) accounted for having sequestered higher amounts of carbon through aboveground and belowground biomass while growing the feedstock. The amount of carbon sequestered while growing the feedstock was -40.92 tonne CO_2e/ tonne BC for stationary units and -77 tonne CO_2e/ tonne BC for portable units. Around 1.88 times more carbon per tonne of biochar was sequestered by portable units while growing the trees during the cultivation period.

If aboveground and belowground carbon is not accounted for in the cultivation stage, the net GWP for portable units is -0.246 tonne CO_2e/ tonne BC while it was lower by 5.36 times for stationary units at -1.318 tonne CO_2e/ tonne BC. This indicates that stationary units (without including aboveground and belowground carbon) can sequester more carbon compared to portable units and also emphasizes that individual production stages for portable units have a higher GWP compared to the alternative. The amount of carbon sequestered for both these systems is -2.508 tonne CO_2e/ tonne BC when 10 tonnes of biochar is applied to agricultural land over a 30-year rotation at the baseline cost (delivered wood price \$25.63/green tonne at 50% moisture content, \$51.26/dry tonne). This is due to utilizing the same chemical composition of feedstock procured and biochar produced through different conversion technologies and assuming that 80% of carbon will remain in the soil for both cases.

The GWP for stationary units per tonne biochar produced is lower during the stages of growing the feedstock, harvesting, chipping, and drying compared to portable units (Figure 6). The GWP per tonne biochar for growing the feedstock and harvesting was higher by 1.88 times for portable units compared to stationary ones. The same trend was noticed for chipping where portable units had a GWP of 0.029 tonne CO_2e /tonne BC whereas it was 0.015 tonne CO_2e/tonne BC (lower by 1.93 times). For drying, stationary units had 3.25 times higher GWP compared to portable units; the figures were 0.038 tonne CO_2e/tonne BC and 0.125 tonne CO_2e/ tonne BC, respectively. When pyrolysis is conducted, portable units have a GWP contribution at 0.025 tonne CO_2e/tonne BC while it was 2.1 times lower for stationary units at 0.012 tonne CO_2e/tonne BC. GWP for transportation of biomass to facilities, transportation of biochar to agricultural lands and application of biochar to cropland were the same per tonne of biochar produced for both stationary and portable units. This is due to having a fixed density for biomass and biochar that will be transported and applied for both these cases.

Table 4.15 GWP per tonne of biochar produced for stationary and portable units

Stages in LCA	GWP (tonne CO_2e / tonne biochar produced)	
	Stationary	Portable
Growing feedstock	0.513	0.964
Harvest	0.575	1.081
Aboveground carbon (AGC)	-25.61	-48.20
Belowground carbon (BGC)	-15.31	-28.80
Chipping	0.015	0.029
Transporting biomass to facility	0.012	0.012
Drying	0.038	0.125
Pyrolysis	0.012	0.025
Transporting biochar to agricultural lands	0.012	0.012
Applying biochar to cropland	0.013	0.013
Carbon sequestered through biochar application	-2.445	-2.445
Net GWP	-42.24	-77.24
Amount of biomass procured at baseline cost	*2.4 million green tonnes*	*4.1 million green tonnes*
Net GWP without AGC & BGC	*-1.318*	*-0.246*
Carbon sequestered during growing feedstock	*-40.92*	*-77.00*

**tonne CO_2e/tonne biochar produced = tonne CO_2e/BC*

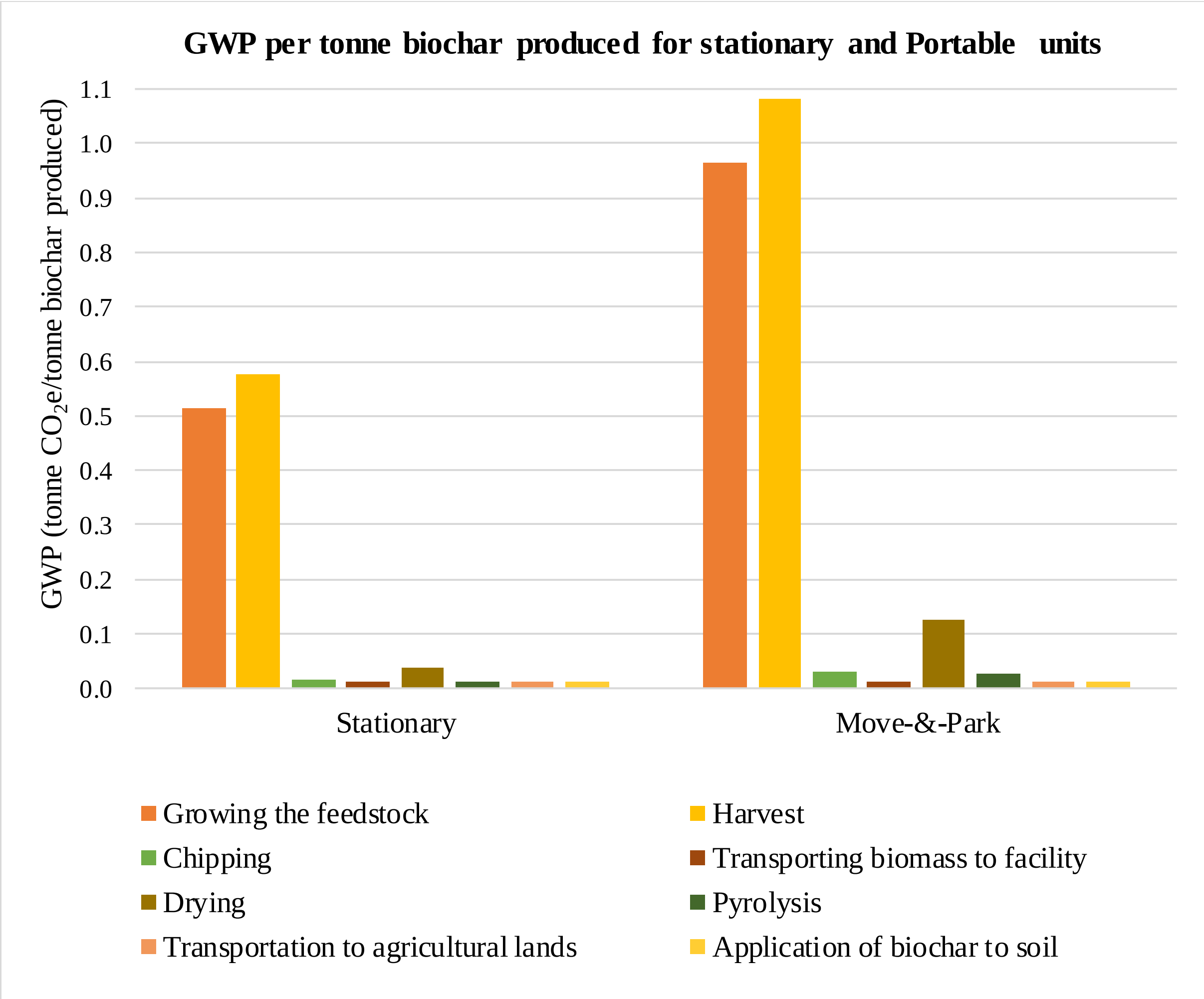

Figure 4.6 Contribution analysis of GWP per tonne biochar produced for stationary and Portable units

Potential biochar demand vs biochar supply through stationary and portable facilities

The amount of biochar produced through stationary units is 386,000 tonnes while it was 1.11 times lower for portable units at 349,000 tonnes (Table 16) Although portable units were able to procure a higher amount of biomass, the amount of biochar produced is lower due to having a lower conversion yield of 18.6% against 35% for stationary units. The economic feasibility study conducted in Chapter 1 of this thesis estimated the potential biochar supply of 465,000 tonnes based on the amount of biomass stationary units were able to procure; this is lower by approximately 17% lower (386,000 tonnes) than what was estimated. For portable units as well, the amount of biochar produced is around 20% lower (349,000 tonnes) than what was initially estimated to be $435,000 tonnes through the economic feasibility study. This is due to the losses involved during chipping (0.5%), storage (3%), transporting, handling, loading, and unloading (~5%) have been accounted for in the LCA which was not done during the economic assessment. However, the primary reason for this difference is due to using procured biomass (5.61%) for running the gasifier, which helps in combusting the tar, char, carbon dioxide and hydrogen gases producing during the process and contributes to operating the pyrolysis reactor.

The amount of biochar demand calculated from the economic analysis was 336,000 tonnes for stationary and 615,000 tonnes for portable units (1.83 times higher). The biochar demand corresponded to the cropland area within the optimized baseline cost ($51.26/dry tonne biomass). We estimated applying 10 tonnes of biochar to agricultural land over a 30-year rotation and assessed how each of these production systems would match up to the estimated biochar demand. Stationary units are able to produce a surplus of biochar (50,000 tonnes) and are able to fulfill estimated biochar demand in agricultural lands within the baseline scenario. Stationary units are able to apply biochar to an additional 15% of agricultural lands with the surplus amount produced. However, it was contrary to the portable systems which had a biochar deficit of 266,000 tonnes and can only apply biochar to 57% of the agricultural lands estimated within the optimized baseline cost scenario. We also calculated the ratio for estimated biochar demand to biochar produced to be 0.87 for stationary units and 1.76 for portable units. The ratio signifies that for stationary units, the biochar demand calculated through the economic feasibility study is 13% lower than the amount of biochar produced (as calculated in the LCA). The surplus amount can be exported to other counties or adjoining states for creating an additional revenue generating stream. On the other hand, for portable units, the estimated biochar demand from the economic assessment is 76% higher than the amount of biochar produced (calculated through the LCA). The figures are an indicator that although portable systems are able to procure more biomass compared to stationary units, they are not able to fulfill the potential biochar demand within the same optimized transportation cost. This is primarily due to their lower conversion yields (18.6% against 35%) and for having to fulfill a higher potential biochar demand at the same optimized transportation cost.

Table 4.16 Comparison of potential biochar demand and supply based on an economic and environmental feasibility study

	Stationary	Portable
Amount of biochar produced	386,000 tonnes	349,000 tonnes
Estimated biochar supply from economic analysis*	465,000 tonnes	435,000 tonnes

Table 4.16 (cont'd)

Estimated biochar demand from economic analysis*	336,000 tonnes	615,000 tonnes
Percentage of estimated biochar demand that can be fulfilled with the amount produced	115%	57%
Amount of surplus/deficit	+50,000 tonnes	-266,000 tonnes
Ratio of estimated biochar demand*: biochar produced	0.87	1.76

**Potential biochar supply and biochar demand have been calculated through the economic feasibility study conducted in Chapter 1 of this thesis. The figures correspond to the baseline scenario where delivered wood price = $25.63/green tonne biomass at 50% moisture ($51.26/dry tonne biomass); GT = green tonnes; DT = dry tonnes.*

Limitations of the study

This LCA has avoided allocation as only one product is considered through the thermal decomposition of biomass and assessed systems based on different reference flows of biomass. We calculated the amount of carbon sequestered based on the application rate of 10 tonnes/acre over a 30-year rotation period, however, if there is a change, the corresponding GWP will also change. The amount of biochar required depends on the type of soil and climate in addition to the type of feedstock used for biomass to biochar conversion. The data quality of the LCA does not reflect the geographic specificity of Michigan for all categories and is an aspect that can help improve the results obtained through this analysis.

Future scope of the study

The potential biochar demand has been estimated using the cropland area within the service area corresponding to the optimized transportation cost. However, a socioeconomic assessment should be conducted with landowners and manufacturers to comprehend their interest in biochar production using biomass. Conducting the LCA has helped in identifying the difference between the estimated biochar supply (economic feasibility study from Chapter 1) and the actual amount that can be produced with the procured biomass after accounting for losses involved in different production stages (calculated through the LCA). Including a human dimensions aspect through a survey will identify the difference between estimated biochar demand and the actual amount of biochar demanded from agricultural stakeholders in Michigan. The data quality in this LCA can be improved in terms of the geographic specificity of Michigan. A lot of assumptions had to be made, primarily due to not having any biochar processing facilities in Michigan and for working with secondary data only. This LCA on GWP for stationary and portable units but other environmental impacts of land-use change, resource depletion, eutrophication, and human toxicity should also be calculated. All these impact categories can play a pivotal role in making financial investments involving biochar technologies and developing climate mitigation strategies. Furthermore, the novelty of this LCA lies in comparing the GWP for biochar as the primary product produced through stationary and portable units. However, the co-production of biochar with bio-oil for both these production systems should also be explored and compared with this LCA when biochar is the primary product. Coproduction of biochar with bioenergy produces less greenhouse gas emissions compared to alternative of biomass to liquid biofuel conversion (C. Lee et al., 2010). Lastly, the production of electricity by combusting the synthetic gases produced through pyrolysis should also be investigated to further identify the environmental impacts of both stationary and portable production technologies.

4.4 CONCLUSION

Having different conversion yields causes the amount of biochar produced through stationary and portable units to have different GWP impacts on the environment. Although portable units are able to procure a higher amount of biomass (4.1 million green tonnes, 1.71 times higher than stationary units) at the same optimized transportation cost, they are only able to fulfill 57% of the potential biochar demand estimated through the economic feasibility study in Chapter 1. On the other hand, stationary units can produce 15% more biochar than estimated and can export it to neighboring counties and adjoining states. It should also be noted that portable units have a higher potential biochar demand compared to stationary units at the same optimized transportation cost; their lower conversion yield (18.6% against 35%) makes it more challenging to fulfill the demand. The amount of biochar supply estimated through Chapter 1 is higher than the results obtained through this LCA. This is due to considering losses that occurred during the production stages of chipping, drying, transporting, handling, and hauling in the LCA. However, the primary reason is because of utilizing 5.61% of the procured biomass to run the gasifier, followed by combusting the tar, char, and gases to produce energy for operating the pyrolysis reactor. The LCA also considered combusting the pyrolytic gases produced during biomass to biochar conversion and used it to run dryer operations for both cases. Harvesting, growing the feedstock, and drying were the biggest contributors to GWP per functional unit (per state of

Michigan (FU)). The amount of carbon sequestered through aboveground and belowground carbon during cultivation was the primary reason for the net GWP to be negative for both stationary and portable systems. Stationary units had a GWP of -14.78 tonne CO2e/FU while it was -14.37 tonne CO2e/FU for portable units. The amount of carbon sequestered due to applying 10 tonnes/acre of biochar as a soil amendment is -2.508 tonne CO2e/ tonne BC over a 30-year rotation at the baseline cost (delivered wood price $25.63/green tonne at 50% moisture content, $51.26/dry tonne). Portable units can sequester 77.24 tonnes CO_2e/tonne BC (1.83 times higher than stationary units which can sequester 42.24 tonnes CO_2e/tonne BC). This corresponds to having procured more biomass and accounting for the aboveground and belowground carbon stocks during cultivation. However, without including these carbon stocks, stationary units are able to sequester 5.36 times more carbon per tonne of biochar, indicating that portable have higher GWP contribution per tonne of biochar when including all emissions from starting from field biomass production to biomass till biochar land application. Overall, stationary unit facilities are superior to would prove to be a better option to produce biochar compared to portable units because of having lower GWP for both per tonne of feedstock and per tonne of biochar.

REFERENCES

Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A review on current status of biochar uses in agriculture. *Molecules*, *26*(18), 5584.

Belay-Tedla, A., Zhou, X., Su, B., Wan, S., & Luo, Y. (2009). Labile, recalcitrant, and microbial carbon and nitrogen pools of a tallgrass prairie soil in the US Great Plains subjected to experimental warming and clipping. *Soil Biology and Biochemistry*, *41*(1), 110-116.

Bergman, R., Sahoo, K., Englund, K., & Mousavi-Avval, S. H. (2022). Lifecycle assessment and techno-economic analysis of biochar pellet production from forest residues and field application. *Energies*, *15*(4), 1559.

Berry, M. D., Sessions, J., & Zamora-Cristales, R. (2018). Subregional comparison for forest-to-product biomass supply chains on the Pacific West Coast, USA. *Applied Engineering in Agriculture*, *34*(1), 157.

Bista, P., Ghimire, R., Machado, S., & Pritchett, L. (2019). Biochar effects on soil properties and wheat biomass vary with fertility management. *Agronomy*, *9*(10), 623.

Blackwell, P., Riethmuller, G., & Collins, M. (2009). Biochar Application to Soil. *Biochar for Environmental Management: Science and Technology*, 207.

Booth, M. (2023, April 7). Will a Colorado biochar company lock up enough carbon to help the planet? *The Colorado Sun*. Available on: https://coloradosun.com/2023/04/07/biochar-carbon-capture-climate-change/. Last accessed on 8th August 2023.

Brassard, P., Godbout, S., Lévesque, V., Palacios, J. H., Raghavan, V., Ahmed, A., ... & Verma, M. (2019). Biochar for soil amendment. In *Char and carbon materials derived from biomass* (pp. 109-146). Elsevier.

Brewer, C. E., & Levine, J. (2015). Weight or volume for handling biochar and biomass. *Biochar J*, *727*, 728.

Brown, T. R., Wright, M. M., & Brown, R. C. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining*, *5*(1), 54-68.

Burt, A., Boni Vicari, M., Da Costa, A. C., Coughlin, I., Meir, P., Rowland, L., & Disney, M. (2021). New insights into large tropical tree mass and structure from direct harvest and terrestrial lidar. *Royal Society Open Science*, *8*(2), 201458.

Cao, C. (2017). Sustainability and life assessment of high strength natural fibre composites in construction. In *Advanced high strength natural fibre composites in construction* (pp. 529-544). Woodhead Publishing.

Celik, A., & Altikat, S. (2022). The effect of power harrow on the wheat residue cover and residue incorporation into the tilled soil layer. *Soil and Tillage Research*, *215*, 105202.

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., ... & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, *145*, 87-99.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., ... & Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology*, *20*(10), 3177-3190.

Chun, Y., Lee, S. K., Yoo, H. Y., & Kim, S. W. (2021). Recent advancements in biochar production according to feedstock classification, pyrolysis conditions, and applications: A review. *BioResources*, *16*(3), 6512.

Cook. B. (2017). *Logging Slash*. Michigan State University Extension. Available on : https://www.canr.msu.edu/news/logging_slash. Last accessed on 8th August 2023.

Cook, P. & Becker, R. (2017)/. State Funding for Wildfire Suppression in the Western U.S. University of Idaho. Available on: https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/cnr/research/PAG/Research/PAGReport37.pdf. Last accessed on 8th August 2023.

Craft, C. (2013). Emergent macrophyte biomass production. *Methods in biogeochemistry of wetlands*, *10*, 137-153.

Curran, M. A. (2006). EPA: Life cycle assessment: Principles and practice. *Scientific Applications International Corporation (SAIC)*.

Curran, M. A. (Ed.). (2016). *Goal and Scope Definition in Life Cycle Assessment.* Springer.

Davies, G., El Sheikh, A., Collett, C., Yakub, I., & McGregor, J. (2021). Catalytic carbon materials from biomass. In *Emerging carbon materials for catalysis* (pp. 161-195). Elsevier.

De la Cruz-Amo, L., Bañares-de-Dios, G., Cala, V., Granzow-de la Cerda, Í., Espinosa, C. I., Ledo, A., ... & Cayuela, L. (2020). Trade-offs among aboveground, belowground, and soil organic carbon stocks along altitudinal gradients in Andean tropical montane forests. *Frontiers in plant science*, *11*, 106.

Delaney, M., & Miles, T. (2019). Economics of mobile and stationary biochar production systems using juniper feedstocks in Oregon. *Corvallis, OR: USDA–ARS, Oregon State University*.

DeLuca, T. H., Gundale, M. J., Brimmer, R. J., & Gao, S. (2020). Pyrogenic carbon generation from fire and forest restoration treatments. *Frontiers in forests and global change*, *3*, 24.

Eggink, A., Palmer, K., Severy, M., Carter, D., & Jacobson, A. (2018). Utilization of wet forest biomass as both the feedstock and electricity source for an integrated biochar production system. *Applied Engineering in Agriculture*, *34*(1), 125.

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., ... & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, *337*, 536-554.

Field, J. L., Keske, C. M., Birch, G. L., DeFoort, M. W., & Cotrufo, M. F. (2013). Distributed biochar and bioenergy coproduction: a regionally specific case study of environmental benefits and economic impacts. *Gcb Bioenergy*, *5*(2), 177-191.

Filbakk, T., Skjevrak, G., Høibø, O., Dibdiakova, J., & Jirjis, R. (2011). The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters. *Fuel Processing Technology*, *92*(5), 871-878.

Fire Management Section (Forest Resources Division). (2021). *Michigan 2021 Wildland Fire Report*. Michigan Department of Natural Resources. Available online : https://www.michigan.gov/dnr/-/media/Project/Websites/dnr/Documents/FRD/fire/Wildland-fire-report.pdf?rev=0de6a8b7103345349e9416e9b12dbfca#:~:text=Fire%20season%20summary,fires%20originated%20on%20private%20property. Last accessed on 8th August 2023.

Fornwalt, P. J., & Rhoades, C. C. (2011). Rehabilitating slash pile burn scars in upper montane forests of the Colorado Front Range. *Natural Areas Journal*, *31*(2), 177-182.

Gao, Y., Shao, G., Yang, Z., Zhang, K., Lu, J., Wang, Z., ... & Xu, D. (2021). Influences of soil and biochar properties and amount of biochar and fertilizer on the performance of biochar in improving plant photosynthetic rate: A meta-analysis. *European Journal of Agronomy*, *130*, 126345.

Shivan, G. C., Miller, R. O., & Potter-Witter, K. A Snapshot of New Woody Biomass Production Potential in Michigan.

Glaser, B., Parr, M., Braun, C., & Kopolo, G. (2009). Biochar is carbon negative. *Nature Geoscience*, *2*(1), 2-2.

Habib, S., & Al-Ghamdi, S. G. (2021). Estimation of above-ground carbon-stocks for urban greeneries in arid areas: Case study for Doha and FIFA World Cup Qatar 2022. *Frontiers in Environmental Science*, *9*, 635365.

Haque, N. (2020). The life cycle assessment of various energy technologies. In *Future Energy* (pp. 633-647). Elsevier.

Haque, N., & Somerville, M. (2013). Techno-economic and environmental evaluation of biomass dryer. *Procedia Engineering*, *56*, 650-655.

Huang, Y., Finell, M., Larsson, S., Wang, X., Zhang, J., Wei, R., & Liu, L. (2017). Biofuel pellets made at low moisture content–Influence of water in the binding mechanism of densified biomass. *Biomass and bioenergy*, *98*, 8-14.

Ingram, D. L. (2012). Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components. *The International Journal of Life Cycle Assessment*, *17*, 453-462.

Jang, W., Page-Dumroese, D. S., & Han, H. S. (2017). Comparison of heat transfer and soil impacts of air curtain burner burning and slash pile burning. *Forests*, *8*(8), 297.

Kachamba, D. J., Eid, T., & Gobakken, T. (2016). Above-and belowground biomass models for trees in the miombo woodlands of Malawi. *Forests*, *7*(2), 38.

Kalabokidis, K. D., & Omi, P. N. (1998). Reduction of fire hazard through thinning/residue disposal in the urban interface. *International Journal of Wildland Fire*, *8*(1), 29-35.

Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T. M., & Dewil, R. (2022). Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chemical Engineering Journal*, *428*, 131189.

Klöpp er, W., & Curran, M. A. (2016). *LCA Compendium-The Complete World of Life Cycle Assessment Series Editors: Goal and Scope Definition in Life Cycle Assessment.*

Langholtz, M. H., Stokes, B. J., & Eaton, L. M. (2016). *2016 billion-ton report: advancing domestic resources for a thriving bioeconomy* (No. DOE/EE-1440). EERE Publication and Product Library, Washington, DC (United States).

Lee, C., Erickson, P., Lazarus, M., & Smith, G. (2010). Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues-FINAL DRAFT Version 2.0. *Olympic Region Clean Air Agency (ORCAA)*.

Lee, Y., Ryu, C., Park, Y. K., Jung, J. H., & Hyun, S. (2013). Characteristics of biochar produced from slow pyrolysis of Geodae-Uksae 1. *Bioresource Technology*, *130*, 345-350.

Leppäkoski, L., Marttila, M. P., Uusitalo, V., Levänen, J., Halonen, V., & Mikkilä, M. H. (2021). Assessing the carbon footprint of biochar from willow grown on marginal lands in Finland. *Sustainability*, *13*(18), 10097.

Liu, Y., Goodrick, S., & Heilman, W. (2014). Wildland fire emissions, carbon, and climate: Wildfire–climate interactions. *Forest Ecology and Management*, *317*, 80-96.

De Gerenyu, V. O. L., Kurganova, I. N., & Kuzyakov, Y. (2008). Carbon pool and sequestration in former arable Chernozems depending on restoration period. *Ekologija*, *54*(4).

Major, J. (2010). Guidelines on practical aspects of biochar application to field soil in various soil management systems. *International Biochar Initiative*, *8*, 5-7.

Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and soil*, *333*, 117-128.

Mašek, O. (2016). Biochar in thermal and thermochemical biorefineries—production of biochar as a coproduct. In *Handbook of biofuels production* (pp. 655-671). Woodhead Publishing.

Mathers, J. (2015). Green Freight Math: How to Calculate Emissions for a Truck Move. *Environmental Defense Fund*.

McLauchlan, K. K., & Hobbie, S. E. (2004). Comparison of labile soil organic matter fractionation techniques. *Soil Science Society of America Journal*, *68*(5), 1616-1625.

Snow, M. (2022, October 11). *How Does Wildfire Impact Wildlife and Forests?* U.S. Fish & Wildlife Service. Available on https://www.fws.gov/story/2022-10/how-does-wildfire-impact-wildlife-and-forests. Last accessed on 8th August 2023.

MSU Forestry Extension Team. (2014). *Forest Types of Michigan: Jack Pine*. Michigan State University Extension. Available on : https://www.canr.msu.edu/resources/forest_types_of_michigan_jack_pine_e3202_11. Last accessed on 8th August 2023.

Mirkouei, A., Mirzaie, P., Haapala, K. R., Sessions, J., & Murthy, G. S. (2016). Reducing the cost and environmental impact of integrated fixed and mobile bio-oil refinery supply chains. *Journal of cleaner production*, *113*, 495-507.

Mohan, D., Sarswat, A., Ok, Y. S., & Pittman Jr, C. U. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. *Bioresource technology*, *160*, 191-202.

Mott, C. M., Hofstetter, R. W., & Antoninka, A. J. (2021). Post-harvest slash burning in coniferous forests in North America: A review of ecological impacts. *Forest Ecology and Management*, *493*, 119251.

Muñoz, E., Curaqueo, G., Cea, M., Vera, L., & Navia, R. (2017). Environmental hotspots in the life cycle of a biochar-soil system. *Journal of Cleaner Production*, *158*, 1-7.

Muralikrishna, I. V., & Manickam, V. (2017). Life cycle assessment. *Environmental management*, *11*(1), 57-75.

Nair, V. D., & Mukherjee, A. (2022). The use of biochar for reducing carbon footprints in land-use systems: prospects and problems. *Carbon Footprints*, *1*(2), 12.

National Interagency Fire Center (NIFC). (2023). *April 2023 Wildfires Report*. National Centers for Environmental Information. Available on : https://www.ncei.noaa.gov/access/monitoring/monthly-report/fire/202304. Last accessed on 8th August 2023.

Noss, R. F., Franklin, J. F., Baker, W. L., Schoennagel, T., & Moyle, P. B. (2006). Managing fire-prone forests in the western United States. *Frontiers in Ecology and the Environment*, *4*(9), 481-487.

Obernberger, I., & Thek, G. (2004). Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. *Biomass and bioenergy*, *27*(6), 653-669.

Ohara, K. D. (2022). *Climate change in the anthropocene*. Elsevier.

Pagliuso, J. D. (2010). Biofuels for spark-ignition engines. In *Advanced direct injection combustion engine technologies and development* (pp. 229-259). Woodhead Publishing.

Pan, S., Gan, L., Jung, J., Yu, W., Roy, A., Diao, L., ... & Choi, Y. (2023). Quantifying the premature mortality and economic loss from wildfire-induced PM2. 5 in the contiguous US. *Science of The Total Environment*, *875*, 162614.

Pelaez-Samaniego, M. R., Mood, S. H., Garcia-Nunez, J., Garcia-Perez, T., Yadama, V., & Garcia-Perez, M. (2022). Biomass carbonization technologies. *Sustainable Biochar for Water and Wastewater Treatment*, 39-92.

Phyllis2, database for (treated) biomass, algae, feedstocks for biogas production and biochar. (2023). *Wood, Jack pine waste (USA)(#880).* TNO Biobased and Circular Technologies Available on : https://phyllis.nl/Browse/Standard/ECN-Phyllis#jack%20pine. Last accessed on 8th August 2023.

Popescu, F., Mahu, R., Ion, I. V., & Rusu, E. (2020). A mathematical model of biomass combustion physical and chemical processes. *Energies*, *13*(23), 6232.

Poudel, J. (2022). *Forest Products Industries' Economic Contributions: Michigan, 2019*. Michigan Department of Natural Resources. Available online : https://www.michigan.gov/dnr/-/media/Project/Websites/dnr/Documents/FRD/industry/economics/MI-Forest-ProductsIndustry-Report_2019.pdf?rev=b96f1f91f5b944f886f69f2670e016b2#:~:text=Michigan%20forest%20products%20industries'%20total,%2413.4%20billion%20(Table%201). Last accessed on 7th August 2023.

Puettmann, M., Sahoo, K., Wilson, K., & Oneil, E. (2020). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production*, *250*, 119564.

Qian, K., Kumar, A., Zhang, H., Bellmer, D., & Huhnke, R. (2015). Recent advances in utilization of biochar. *Renewable and Sustainable Energy Reviews*, *42*, 1055-1064.Rhoades, C. C., Fornwalt, P. J., Paschke, M. W., Shanklin, A., & Jonas, J. L. (2015). Recovery of small pile burn scars in conifer forests of the Colorado Front Range. *Forest Ecology and Management*, *347*, 180-187.

Rosas, J. G., Gómez, N., Cara, J., Ubalde, J., Sort, X., & Sánchez, M. E. (2015). Assessment of sustainable biochar production for carbon abatement from vineyard residues. *Journal of analytical and applied pyrolysis*, *113*, 239-247.

Sarkar, D., Sinha, A. K., Danish, S., Bhattacharya, P. M., Mukhopadhyay, P., Salmen, S. H., & Datta, R. (2021). Soil organic carbon and labile and recalcitrant carbon fractions attributed by contrasting tillage and cropping systems in old and recent alluvial soils of subtropical eastern India. *PloS one*, *16*(12), e0259645.

Sahoo, K., Bilek, E., Bergman, R., & Mani, S. (2019). Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. *Applied Energy*, *235*, 578-590.

Santín, C., Doerr, S. H., Merino, A., Bucheli, T. D., Bryant, R., Ascough, P., ... & Masiello, C. A. (2017). Carbon sequestration potential and physicochemical properties differ between wildfire charcoals and slow-pyrolysis biochars. *Scientific reports*, *7*(1), 11233.

Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., Van Diemen, R., McCollum, D., ... & Malley, J. (2022). Climate change 2022: Mitigation of climate change. *Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*, *10*, 9781009157926.

Sokhansanj, S., & Webb, E. (2016). Evaluating industrial drying of cellulosic feedstock for bioenergy: a systems approach. *Biofuels, Bioproducts and Biorefining*, *10*(1), 47-55.

Spinelli, R., & Magagnotti, N. (2014). Determining long-term chipper usage, productivity and fuel consumption. *Biomass and Bioenergy*, *66*, 442-449.

Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., de Macêdo, J. L. V., Blum, W. E., & Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and soil*, *291*, 275-290.

Stelte, W., Holm, J. K., Sanadi, A. R., Barsberg, S., Ahrenfeldt, J., & Henriksen, U. B. (2011). Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. *Fuel*, *90*(11), 3285-3290.

The Nature Conservancy in Michigan. (2021). *FORESTS*. The Nature Conservancy in Michigan. Available on https://www.nature.org/content/dam/tnc/nature/en/documents/MI2021Resilientforests.pdf. Last accessed on 8th August 2023.

The Wood Database. (2023). Jack Pine. Eric Meier. Available on : https://www.wood-database.com/jack-pine/. Last accessed on 8th August 2023.

Trubetskaya, A., Johnson, R., Monaghan, R. F., Ramos, A. S., Brunsvik, A., Wittgens, B., ... & Budarin, V. (2021). Combined analytical strategies for chemical and physical characterization of tar from torrefaction of olive stone. *Fuel*, *291*, 120086.

Wang, Z., & Liu, F. (2021). Environmental assessment tools. In *Industrial Ventilation Design Guidebook* (pp. 435-448). Academic Press.

Weber, K., & Quicker, P. (2018). Properties of biochar. *Fuel*, *217*, 240-261.

Weidema, B. P., & Wesnæs, M. S. (1996). Data quality management for life cycle inventories—an example of using data quality indicators. *Journal of cleaner production*, *4*(3-4), 167-174.

Yang, Q., Mašek, O., Zhao, L., Nan, H., Yu, S., Yin, J., ... & Cao, X. (2021). Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation. *Applied Energy*, *282*, 116275.

Zou, X. M., Ruan, H. H., Fu, Y., Yang, X. D., & Sha, L. Q. (2005). Estimating soil labile organic carbon and potential turnover rates using a sequential fumigation–incubation procedure. *Soil Biology and Biochemistry*, *37*(10), 1923-1928.

CHAPTER 5 : CONCLUSION

This study has been able to compare the two different biomass procurement approaches, stationary and portable, in Michigan and recognize respective strengths and weaknesses based on the optimization of transportation costs. The upper peninsula has a larger proportion of forests compared to the lower peninsula, indicating that more biomass would be available for procurement. However, when analyzed with the road transportation network data on ArcGIS using a cost optimization approach, the lower peninsula is equipped to procure more biomass. The lower peninsula has a higher potential demand for biochar compared to the upper peninsula due to having more cropland there, and hence, requires more biochar per acre as a soil amendment.

The biomass supply through portable mobile facilities is larger compared to stationary ones through the optimization of transportation costs when stumpage is $0/green ton. To meet the same potential biochar demand, a higher number of Portable processing facilities will be required compared to the stationary ones, because of the former's lower production capacity. For all cost scenarios, the amount of biomass procured through Portable facilities is higher for both the peninsulas, emphasizing that it is more economically feasibility where the amount of biomass procured is the primary concern.

However, when prioritizing biochar production and application, the conversion yields of Portable facilities fall short despite having more biomass going into the conversion process. Portable units can procure a higher amount of biomass. They are not able to fulfill the potential biochar demand estimated through the economic feasibility study. On the other hand, stationary units can produce biochar than estimated. The amount of carbon sequestered through aboveground and belowground carbon during cultivation were the primary reasons for the net GWP to be negative for both stationary and Portable systems.

In recapitulation, the study helps us bridge the knowledge gap on low-value biomass utilization for biochar production in Michigan. The novelty of this study lies in optimizing transportation costs for biochar production and utilization as a soil amendment followed by comparing the economic and environmental feasibility of stationary and Portable facilities in Michigan. Establishing a potential biochar market for unused forest biomass in Michigan will not only help combat the climate challenges but also open doors for practicing natural resource-based climate strategies across the Great Lakes region.