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Biochar and Climate Change Mitigation: Economic Models and Regional Impacts

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# Biochar and Climate Change Mitigation: Economic Models and Regional Impacts

A Dissertation submitted in partial satisfaction of the requirements
for the degree Doctor of Philosophy

in
Environmental Systems

by
Maryam Nematian

Committee in charge:
Professor Gerardo Diaz, Chair
Professor Rebecca Ryals
Professor Josué Medellín-Azuara
Professor John Ng'ombe

2023

This dissertation by Maryam Nematian, titled “
Biochar and Climate Change Mitigation: Economic Models and Regional Impacts” is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

**Gerardo Diaz, Chair** Date

**Rebecca Ryals** Date

**Josué Medellín-Azuara** Date

**John Ng'ombe** Date

University of California Merced

2023

## Dedication

Dedicated to my husband, the light of my life.

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# Acknowledgments

I would like to thank my advisors Dr. Catherine Keske and Dr. Rebecca Ryals for their invaluable guidance and support throughout my academic journey. To Dr. Keske: thank you for trusting in me and giving me the chance to start my Ph.D. journey. I am truly grateful for the countless hours you have devoted to helping me. To Dr. Ryals: I really appreciate all your help at the time I needed it most. Your support is the main reason I am able to finish my thesis.

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Chapter 3, in full, is a reprint of the material as it appears in Nematian, Maryam, John N. Ng'ombe, and Catherine Keske. "Sustaining agricultural economies: regional economic impacts of biochar production from waste orchard biomass in California's Central Valley." Environment, Development and Sustainability (2023): 1-21. The dissertation author was the primary researcher and author of this paper.

Chapter 4 is currently being prepared for submission for publication of the material. The dissertation author is the primary researcher and author of this material.

## Curriculum Vitae

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## EDUCATION

Ph.D. Student in Environmental Systems *August 2019–November 2023*
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Bachelor of Science in Civil Engineering *September 2009 –June 2013*
*Guilan University, Guilan, Iran.*

## PUBLICATIONS

**Nematian, Maryam, Catherine Keske, and John N. Ng'ombe. "A techno-economic analysis of biochar production and the bioeconomy for orchard biomass." Waste Management 135 (2021): 467-477.**

- We developed an enterprise budget and performed a stochastic analysis to estimate the cost of biochar production using portable units.
- The objective of this research is to offer a sustainable and economically viable solution for crop residue management, benefiting farmers.
- We found that biochar production can help with establishing a bioeconomy in California.

**Nematian, Maryam, John N. Ng'ombe, and Catherine Keske. "Sustaining agricultural economies: regional economic impacts of biochar production from waste orchard biomass in California's Central Valley." Environment, Development and Sustainability (2023): 1-21.**

- We upgraded the IMPLAN database to add biochar as a new industry and studied the potential economic impacts of biochar production in underserved communities.
- The results of this paper can be used by policymakers to explore strategies for enhancing the economic sustainability of biochar production in Central Valley, California.

**Nematian, Maryam, and Catherine Keske. "The Social Discount Rate for Biochar Projects in the United States." Fall Meeting 2022. AGU, 2022.**

- We developed a social discount rate model that considers environmental justice indexes.
- This suggested rate is put forth as the recommended parameter to be employed in the cost-benefit analysis of biochar.

- Utilizing this rate allows for a more accurate and comprehensive assessment of the economic implications and potential advantages associated with biochar.

## TEACHING AND RESEARCH EXPERIENCE

- Research Assistant (RA), 2019-Present, University of California Merced, California, USA.
- Instructor of record (2022), University of California Merced, California, USA.

## COMPUTER AND PROGRAMMING SKILLS

- Professional: IMPLAN, @RISK, Excel, ETABS, SAP, SAFE, AutoCAD
- Intermediate: Python, R, ArcGis

## HONORS AND AWARDS

- CADE Teaching Fellowship Fall 2022.

I have been awarded the CADE Teaching Fellowship Fall 2022 and taught two sections of the Inclusive Innovation course at the Center for Advancing Diversity in Engineering.

- Awarded a grant by California Strategic Growth Council, 2019-2022.

I was part of a “Mobile Biochar Production for Methane Emission Reduction and Soil Amendment” project. The project has been awarded a grant by the California Strategic Growth Council.

- Ranked First- Environmental Engineering, Sharif University of Technology, Tehran, Iran, 2017.

## RELEVANT COURSEWORK

- Energy Policy (A)
- Systems Thinking (A)
- Coupled Natural Human System Foundation II (A)
- Engineering Economic Analysis (A+)
- Environmental Data Analysis (A+)

## EXTRACURRICULAR ACTIVITIES

- I mentored first-year students to develop research for a program called FACTS. It stands for San Joaquin Valley Food and Agriculture Cyber Informatics Tools and Science and was funded by the United States Department of Agriculture.
- Course Project: Analyzing the Economics of California’s cap-and-trade program, conducting an analysis of Senate Bill No. 1383, and exploring policies aimed at reducing methane emissions from dairy manure management operations in California.
- Writing quarterly reports for the economic section of biochar research for the California Strategic Growth Council.

## Abstract

### Biochar and Climate Change Mitigation: Economic Models and Regional Impacts

by

Maryam Nematian
Doctor of Philosophy in Environmental Systems
University of California Merced, 2023

This thesis explores the diverse aspects of biochar production, its economic assessment, and its importance in mitigating climate change while supporting sustainable regional economic growth. Biochar, a carbonaceous biomass product, is gaining increasing prominence as an effective solution for curbing greenhouse gas emissions stemming from conventional agricultural practices.

This research adopts a comprehensive approach that covers various dimensions of biochar. First, it emphasizes the necessity of shifting from the environmentally harmful practice of crop residue open burning to the more sustainable avenue of biochar production. Through a techno-economic analysis, the study reveals the range of production costs under uncertainty. Results from the first study show a probable range of biochar production costs between \$448.78 and \$1,846.96 (USD) $Mg^{-1}$, with a 90% probability that costs will range between \$571 and \$1,455 $Mg^{-1}$. A sensitivity analysis shows that production costs are most responsive to biochar production rates.

Second, showing the significance of regional economic assessments for biochar projects. Recognizing the lack of a dedicated industry classification for biochar, innovative methodologies are employed to estimate the direct, indirect, and induced economic impacts of biochar production in Central Valley, California. Results suggest that depending on the biochar price and conversion rates, biochar would create between 16.56 to 17.69 new full-

and part-time jobs per year that would contribute between $1.2 to $5.75 million per year to labor income. Biochar production would add to the Gross Domestic Product (GDP) about $106,295 ($5.2 million) per year with a conversion rate of %15 (%35) and a biochar price of $280 ($2,512) per metric ton. Similarly, biochar's impacts on gross output would be positive, regardless of the biochar conversion rate and price, which suggests the need for more investment in the sector. We find that all regions would benefit in terms of employment, labor compensation, value addition, and gross output though Madera County would have the least economic returns. Meanwhile, Fresno County with the most biomass would have the most economic impacts suggesting that policy should be directed at encouraging biomass production and marketing in areas with the most biomass.

Third, highlighting the critical importance of selecting the appropriate discount rate when evaluating biochar projects, particularly with a focus on climate change mitigation potentials. Two novel environmental-economic discounting models are used, one rooted in a modified Ramsey formula and the other in the Consumption Capital Asset Pricing Model. The first model yields a discount rate of 1.7%, while the second model suggests a declining rate of 5.96%. We recommend incorporating both rates in the biochar cost-benefit analysis and conducting a sensitivity analysis for a more comprehensive assessment.

In summary, this thesis addresses biochar economics from different perspectives, namely, its economic evaluation, its vital role in addressing climate change, and its regional impact. The outcomes confirm the feasibility of transitioning towards a circular bioeconomy, highlight the regional economic benefits associated with biochar production and propose a nuanced discounting framework to ensure precise project evaluation. This research contributes to the development of sustainable practices, economic growth, and the simultaneous resolution of pressing environmental concerns.

# Chapter 1 Introduction

## 1.1. Background

Biochar is a carbon-rich material produced by biomass pyrolysis which involves the thermal decomposition of organic materials in an environment with minimal or no oxygen (Lehmann & Rondon, 2006). The heat treatment applied to organic biomass during biochar production is responsible for its large surface area and its unique capacity to remain in soils with minimal biological decomposition (Hunt et al., 2010; Lehmann & Rondon, 2006). These two characteristics of biochar make it unique compared to other soil amendments and enable biochar to adsorb or retain nutrients and moisture (Glaser et al., 2002; Hunt et al., 2010; Lehmann & Rondon, 2006).

Although biochar recently has gained increasing attention, its historical roots can be traced back to indigenous communities residing in the Amazon Basin. These communities developed remarkably fertile soils, referred to as Terra Preta, meaning the black soil of the Indians (Glaser et al., 2001). The black carbon found in charcoal is regarded as a main component of this dark soil, capable of enduring in the soil for a millennium or more (Chen et al., 2019). Research has demonstrated that crops cultivated in these soils produce three times the amount of grain compared to nearby regions (Tenenbaum, 2009).

Biochar provides a wide range of advantages at the nexus of agriculture, environment, and the economy. Environmental benefits include reduced nitrous oxide (Liu et al., 2017; X. Liu et al., 2013; Zhang et al., 2010) carbon dioxide and methane emissions (Karhu et al., 2011; Spokas & Reicosky, 2009; Zhang et al., 2012).

Other potential benefits include reduced soil bulk density, improved water retention ability, and reduced leaching of soil nutrients (Laird et al., 2009; Lehmann et al., 2011).

These benefits have strengthened the calls for increased biochar soil amendment to both agricultural and forest soils across the world particularly in regions abundant in biomass resources.

Despite all the potential benefits, the biochar market is still in its infancy, and data regarding its economic viability is limited. As with all new technologies, there are uncertainties in the development and deployment of biochar, which has caused producers to avoid investing in this sector and scale up their production volume. These uncertainties include biochar's emissions abatement potential, as well as its impact on different crops and soils. Field experiments examining the effects of biochar as a soil amendment are yielding diverse outcomes, ranging from no apparent impact (Steiner et al., 2004) to a threefold increase in grain yields (Chan et al., 2007). Moreover, while it is feasible to assess the short-term carbon sequestration potential of biochar, investigating its long-term presence in the soil remains currently impossible (Pratt & Moran, 2010). Figure 1-1 shows the uncertainties in biochar application in agriculture.

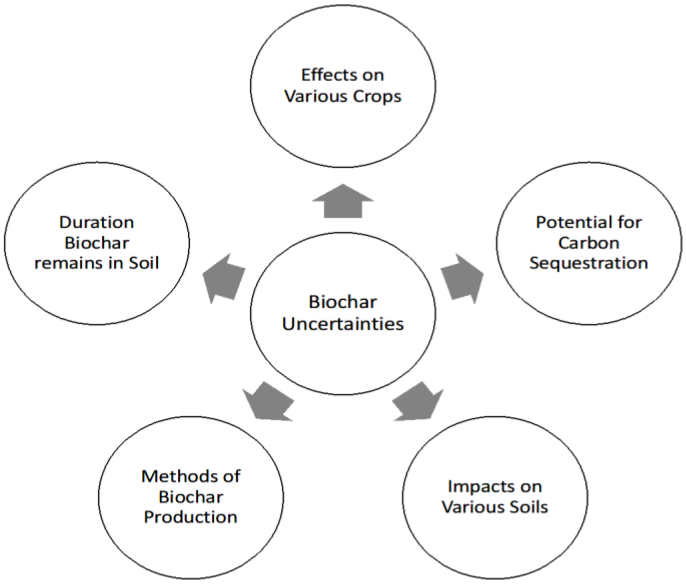

*Figure 1-1 Uncertainties in biochar application in agriculture*

Within this thesis, I try to address these uncertainties and advocate for the utilization of biochar as a cornerstone solution to foster sustainable agricultural practices. This dissertation demonstrates how biochar production from biomass waste can lead to the development of a circular economy.

### 1.2. Research Motivation and Objectives

Agricultural management practices, like open field burning and manure management, can emit high levels of greenhouse gases, including methane and nitrous oxide that can lead to negative externalities such as climate change through different processes.

The annual methane and nitrous oxide emissions have increased by 14 percent and 16 percent from 1990 to 2020, respectively (EPA, 2022). According to the Environmental Protection Agency, in 2020, the agriculture sector was responsible for 10 percent of the total U.S. greenhouse gas emissions (EPA, 2022). This increasing trend of emissions highlights the importance of researching and planning alternative management techniques. Therefore, motivation behind this thesis lies in developing a sustainable approach to manage agricultural waste while simultaneously mitigating greenhouse gas emissions.

This dissertation shows the potential economic feasibility of biochar production using economic analysis that considers uncertainty in different scenarios by accounting for environmental externalities, and adjustments to the social discount rate. I addressed this problem in three separate sections, each of which incorporates uncertainty into biochar economic analysis. Study 1 calculates the cost of converting crop residue to biochar using a portable unit. As a first step in analyzing the economic feasibility of biochar, we used a stochastic method to factor in the uncertainties in the biochar production costs. To do this, we defined distributions for each uncertain parameter using available data and estimated the range of production costs (Nematian et al., 2021). The results of the analysis show that production costs range between \$448.78 and \$1,846.96 $Mg^{-1}$ of biochar. This study offers a tool to estimate the biochar production costs under uncertainty to help producers/farmers to understand the probable range of costs before the outset of the project.

Study 2 utilizes the simulations in study 1 to evaluate the regional economic impacts of introducing the biochar market to Central Valley, California. The results can help to fully comprehend the potential impacts that biochar can have on local economies, in terms of cash flows, employment, and environment. This chapter provides a complete evaluation of the impacts of biochar on jobs, industry output, and total value added to the economy. This information can steer policymakers to support the growth of the biochar market by providing subsidies and incentives that may correct for market inefficiencies, such as externalities from greenhouse gas emissions.

The final study provides a discounting model to capture the economic and social costs and benefits of biochar production. In simple economic terms, biochar is considered an economically viable product when the benefits outweigh the costs. However, calculating costs and benefits associated with biochar is not a straightforward process. Biochar production using portable pyrolysis systems is a new technology and there are many uncertainties regarding costs that may occur during the production phase (which I introduced in study 1). Calculating biochar benefits also have many obstacles since the biochar impacts depend on crop and soil type. Moreover, it is unknown how long the soil benefits will last, highlighting the importance of the rate that should be used to discount future cash flows. To account for all economic and social costs and benefits we propose a discounting model that is tailored to the biochar industry. One of the main reasons that the biochar market, with all of its potential benefits, has ostensibly not yet taken off is the lack of financial profitability. The discount rate proposed in this chapter addresses this challenge by providing a realistic economic analysis that may lead to the development of the biochar market.

In sum, the primary objectives of this thesis are as follows:

- To calculate the cost of biochar production in Central Valley California, considering various factors such as feedstock types, production methods, and operational expenses.
- To estimate the regional economic impacts of biochar production using IMPLAN, taking into account direct, indirect, and induced effects on the local economy.
- To explore and analyze the social discount rates applicable to biochar adoption in agricultural practices, considering the long-term benefits and costs associated with its use.

### 1.3. Structure of the Thesis

This thesis is organized into five main chapters, as follows:

Chapter 1 (this chapter) provides the introduction, presenting the background, rationale, and research objectives. Chapter 2 details the methodology and findings related to the calculation of biochar production costs in Central Valley California. Chapter 3 presents the methodology and results of estimating the regional economic impacts of biochar production using IMPLAN.

Chapter 4 delves into the estimation of social discount rates for biochar, discussing the relevant theories and empirical approaches. Chapter 5 offers a comprehensive discussion of the research findings, their implications, and concludes the thesis.

### 1.4. The region of study

In Chapter 2 and Chapter 3 of this thesis, the study area is Central Valley, California. The unique properties of the Central Valley, California make it an ideal place to produce and apply biochar. The abundance of biomass waste and dependence of the local economy on agriculture are two important motivations for biochar use in this region.

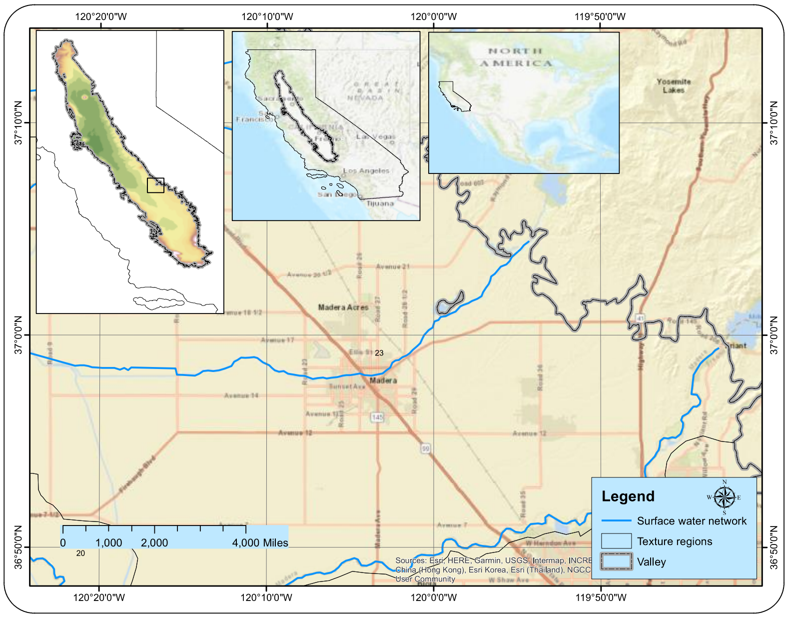

*Figure 1-2 Map of Central Valley, California*

The Central Valley of California is a region with a unique agricultural landscape, contributing significantly to both state and national agricultural production. However, the region faces several challenges, including soil degradation, water scarcity, and the need to reduce greenhouse gas emissions. Biochar, with its soil-enriching properties and carbon sequestration potential, offers a compelling solution to address these challenges.

Understanding the cost of biochar production, its economic impact on the region, and the social discount rates associated with its adoption are crucial steps in determining the feasibility and sustainability of integrating biochar into Central Valley California's agricultural practices. Through a meticulous examination of this region, the thesis endeavors to provide insights and draw parallels to broader global challenges

## 1.5. Conclusion

This dissertation will attempt to propose a solution for the biochar market inefficiency by embedding the uncertainty in the analysis and accounting for equity and risk in the discount rate. Consequently, the result will help the biochar crop residue management system become more efficient, more actively studied, and ultimately establish the biochar market with the help of regulation and funding that addresses current market inefficiencies.

The questions we try to answer in this thesis are the following:

- What is the total cost of biochar production using portable pyrolysis units in the presence of uncertainty?
- How can the production of biochar contribute to the development of a sustainable circular bioeconomy?
- What are the regional impacts of biochar production on underserved communities?
- What key factors influence the overall positive economic returns at a regional level in biochar production?
- How should the social discount rate be selected, considering varying assumptions in biochar projects?

- How does the incorporation of risk factors affect the social discount rate in biochar production initiatives?

# Chapter 2 A Technoeconomic Analysis of Biochar Production and the Bioeconomy for Orchard Biomass

Note: This chapter is a stand-alone paper published in Waste Management Journal.

Citation: Nematian, M., Keske, C., & Ng'ombe, J. N. (2021). A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Management, 135, 467–477. https://doi.org/10.1016/j.wasman.2021.09.014

## 2.1. Abstract

It is well established that the global practice of burning crop residues, such as orchard biomass, harms human health and the environment. A bioeconomy for orchard biomass may reduce open burning, facilitate the recovery of nutrients that improve soil health, and boost economic growth. We present a techno-economic analysis for converting orchard waste into biochar, a charcoal-like substance that shows promise for improving soil health, but that is considered an experimental product with emerging efficacy and limited market demand. We impute values derived from a cost analysis of biochar production in California's Central Valley into a regional economic input-output model to demonstrate economic growth and a bioeconomy for biochar made with orchard waste. Results from a stochastic Monte Carlo simulation show a probable range of biochar production costs between \$448.78 and \$1,846.96 (USD) $\mathrm{Mg}^{-1}$, with a 90% probability that costs will range between \$571 and \$1,455 $\mathrm{Mg}^{-1}$. A sensitivity analysis shows that production costs are most responsive to biochar production rates. A modifiable Excel-based biochar enterprise budget that includes fixed and variable biochar production costs is available. The regional economic analysis demonstrates positive economic growth as defined by job creation, labor compensation, value-added product, and gross output. Stochastic cost estimates and net positive regional economic impacts support the economic feasibility of a circular bioeconomy for waste orchard biomass when coupled with governmental policy initiatives.

Results may contribute to developing a circular bioeconomy for biochar and orchard biomass in the study region and elsewhere in the world.

### 2.2. Introduction

The agricultural practice of burning crop residues serves as one of the greatest sources of greenhouse gas emissions (GHG) and deleterious respiratory human health impacts worldwide (Bhuvaneshwari et al., 2019; Hou et al., 2019; Intergovernmental Panel on Climate Change, 2007).

Crop residues are carbon-based materials such as orchard and vineyard pruning, straw, nutshells, pits, and hulls, generated during crop harvesting and processing(Adhikari et al., 2018; Mohammed et al., 2018). Crop production and crop residue burning have risen to keep pace with accelerated global food demand and population, which has grown three-fold over the past 50 years and is expected to continue in upcoming decades (Cherubin et al., 2018; Food and Agriculture Organization (FAO), 2017; Lal, 2005). The FAO (2020) notes that crop residue burning has risen over the past twenty years across all continents except Oceania. Over the ten-year period from 2003 to 2013, crop residues rose by one-third worldwide, totaling 5 Pg in 2013 (Cherubin et al., 2018; Lal, 2005). Sustainable crop residue management is clearly a global concern.

Crop residue burning is frequently the lowest cost agricultural management option (Hou et al., 2019) to clear fields for the next planting season and to control pests (Raza et al., 2019). Approximately 50% of crop residues are burned before the next farming season (Mohammed et al., 2018). Alternatively, crop residues can be composted for fertilizer or animal bedding, left atop the soil to decompose, or eventually become incorporated into the soil through conservation tillage practices. It follows that open burning may be reduced if crop residues are managed as value-added, rather than waste products. We propose creating biochar from waste orchard residues as an alternative to reduce open burning and to create a circular bioeconomy for orchard crop residues. Biochar is a charcoal-like, high-carbon sub- stance produced at high temperatures through biomass pyrolysis (Maroušek et al., 2019). Besides significantly reducing health and other negative consequences from less air pollution, experiments, and field trials show that, under certain conditions, applying biochar as a soil amendment may increase crop yields and sequester carbon (W. Li et al., 2017). Adding biochar as a soil amendment may reduce soil density and stiffness (Ajayi & Horn, 2016; Grunwald et al., 2017). This may correspondingly reduce soil resistance to plowing and other agrotechnical operations, thereby enabling agricultural producers to reduce diesel fuel consumption (Lu et al., 2014). Environmental benefits include reduced nitrous oxide ($N_2O$) (W. Liu et al., 2017; X. Liu et al., 2013; Zhang et al., 2010) carbon dioxide ($CO_2$) and methane ($CH_4$) emissions (Karhu et al., 2011; Spokas & Reicosky, 2009; Zhang et al., 2012).

Despite preliminary evidence of improved crop yields, managerial cost savings, and environmental benefits, the biochar market is nascent and market transactions are negligible (Campbell et al., 2018; Maroušek et al., 2019). Biochar production has not been a resoundingly profitable business venture, in part due to high fixed and variable costs that are commensurate with a natural monopoly (Skapa, 2012). Insufficient market demand makes cost recovery difficult and creates inability to capitalize on the value of environmental benefits. Biochar has been adopted in rural regions of Asia and Europe (Maroušek et al., 2019; Olarieta et al., 2011) but most households use biochar as a substitute for charcoal. Often, the on-spot profit from using biochar for energy utilization exceeds soil amendment benefits computed over long payback periods (Maroušek et al., 2018; Vochozka et al., 2016). Large-acre farmers across the globe remain unaware or skeptical about biochar benefits (Bezerra et al., 2019; Wu et al., 2017), though there is some commercial demand for home gardening (Field et al., 2013). Maroušek et al. (2019) note that many countries either legally restrict or limit biochar use. Meyer et al. (2017) cite tight regulation and performance verification standards where biochar is considered an experimental product despite a substantial pool of patents (Peiris et al., 2017) and two decades of a burgeoning body of literature promoting the product (El-Naggar et al., 2019).

Though most commercial biochar enterprises are not yet financially viable (Hašková, 2017), this could quickly change with increasingly rigorous GHG emission regulation, and increased biochar demand due to emerging soil health and crop yield efficacy, and falling costs that typically accompany new technologies (Ajayi & Horn, 2016; Ennis et al., 2012; Grunwald et al., 2017; Keske et al., 2019; W. Li et al., 2017; Mardoyan & Braun, 2015; Maroušek et al., 2019, 2020; Mohan et al., 2018). Once the net benefits of biochar production and adoption are shown as cost-competitive management alternatives to crop residue burning, a circular bioeconomy for biochar production can emerge. To get started, the transition to a circular bioeconomy will likely require a targeted financial investment.

With the goal of improving the cost-effectiveness of biochar production and advancing the nascent market for biochar production, this chapter presents a techno-economic analysis of biochar production costs for orchard waste in California’s Central Valley. This region has approximately 8% of the U.S. agricultural output, and 25% of the nation’s food is produced here, including a high percentage of the nation’s tree nuts and nearly 100% of almonds (Faunt et al., 2009). We conduct a Monte Carlo simulation to demonstrate the impacts of uncertainty on biochar production from orchard crop residues to reduce production risk and foster entrepreneurship. We demonstrate that a circular bioeconomy from orchard waste is feasible in the study region, by imputing biochar production values calculated through an enterprise budget into a regional IMpact Analysis for PLANning model (IMPLAN, 2022) to evaluate the economic impacts of biochar production on gross output, income, employment, and value-added output in selected counties in the case study region with orchard biomass and biochar production capacity. If a bioeconomy for biochar production from orchard waste is shown to be economically viable in the study region as an alternative to crop residue burning, there is potential to expand a bioeconomy for biochar elsewhere in the world where there is a critical need to reduce biomass burning, improve soil health, and reduce GHG emissions. To the best of our knowledge, no study provides cost estimates for biochar production under uncertainty with the goal of establishing a bioeconomy. We hypothesize that a range of feasible cost estimates that consider uncertainties associated with biochar production, and that demonstrate value-added product, will foster a bioeconomy.

In the sections that follow, first, we elaborate on biochar's potential to contribute to a circular bioeconomy. Policies relevant to the study region's agricultural waste management and biochar production are also discussed. Materials and methods are in section 2.4, while section 2.5 contains results of the stochastic analysis and regional economic analysis of biochar production. Conclusions are presented in Section 2.6.

### 2.3. Biochar's Contribution to a Bioeconomy

The Linear Economy, comprised of the traditional 'take-make-use-dispose' model of production and consumption, needs to be reworked for agricultural production to keep pace with the world’s projected population and increased demand for food. Burning waste crop residues may be a cost-effective management option in a linear model that overlooks adverse environmental effects and biomass nutrients. Given the anticipated scale for global food production and GHG mitigation, it’s unlikely that farmers and society will be able to ignore these costs and benefits for much longer. The European Commission Circular Economy Strategy and “Closing the Loop” Action Plan (European Commission, 2015) note the high value of bio-based resources and biochar specifically that may lead to a circular bioeconomy (European Commission, 2012; Kourmentza et al., 2018). A “circular bioeconomy” is defined as the overlap of the circular economy and bioeconomy (Carus & Dammer, 2018), an innovative research-based approach to optimize the sustainable management and utilization of bio-based resources (Banu et al., 2020). Carus & Dammer (2018) suggest that the European Union’s 2012 bioeconomy and 2015 circular economy were both connected to biologically originated products, biomass, and food waste. The Institute for European Environmental Policy (2018) contends that the delivery of a circular bioeconomy was created to fulfill the United Nation’s Sustainable Development Goals (SDGs) and commitments to both sustainable consumption and reduced GHG emissions.

Though biochar fits well in the circular bioeconomy concept, economic viability and market competitiveness are necessary to facilitate broader scale biochar production and agricultural sector adoption. Achieving a better understanding of production costs helps entrepreneurs to develop a competitive advantage in biochar production, and eventually drive demand for the bioeconomy. Fear of failure is an obstacle to entrepreneurship and new product adoption (Nefzi, 2018); cost data and uncertainty models like those presented in our analysis, may address such concerns. Technological innovation can help shorten production time, leading to cost competitiveness and higher profit (Urbancova, 2013). To this point, our study proposes to produce biochar locally, in rural locations using portable pyrolysis units instead of a centralized facility. The mobile pyrolysis technical innovation may improve production efficiencies by reducing feedstock transportation costs in rural regions where food is grown. Since there is a high concentration of tree nut production and biomass burning in the study region (McCarty et al., 2009), the enterprise budget production, stochastic analysis, and a regional economic model provide proof of concept testing that may reduce uncertainty and facilitate biochar production that can be replicated with orchard biomass elsewhere. In sum, our study adds to the global interest in advancing biochar production (Qambrani et al., 2017) and improving the cost competitiveness of biochar production to facilitate a bioeconomy.

### ***2.3.1. Study Area***

California's Central Valley serves as a relevant case study due to the region's high agricultural productivity with orchard crops specifically, the high prevalence of open burning of crop residue, and increasingly rigorous air quality regulation standards. Conditions are ripe to establish a bioeconomy from crop residue. California state agencies have implemented numerous policies to reduce open burning, though it remains the state's most common crop residue management practice. Senate Bill-705 requires a valid permit designated by the State Air Resources Board to burn agricultural residues (California Senate Bill No. 705, 2003) and Smoke Management Regulations provide guidelines to air quality management districts to control agricultural residue burning (Title 17 of the California Code of Regulations, 2001). Simultaneously, a series of laws enacted in California target 40% and 80% reductions in the state's GHG emissions including those produced by agricultural crop residues, from 1990 levels by 2030 and 2050 with the hope of mitigating global climate change (Keske, 2020).

Despite these regulations, alarming air pollution levels in the Central Valley continue, in part due to the high biomass transportation costs and poor economic feasibility for value-added biomass products. Twenty- three solid-fuel biomass power plants operate in 17 counties across California with a capacity of producing approximately 532 MW of electricity, though biomass power plants are shutting down periodically due to the high expenses of transporting biomass from diffuse sources (Mayhead & Tittmann, 2012). Technological innovation, such as mobile pyrolysis units, holds promise for processing crop residues on-site to avoid transportation costs and potentially generate a value-added product. California is known as a leader in implementing new environmental policies and facilitating entrepreneurship (Vogel, 2019). Taken together, employing policies that support converting agricultural waste into biochar encourages entrepreneurship that can lay the foundation for the global use of biochar.

### *2.3.2. U.S. policies supporting biochar production*

Policies that encourage biochar production may nudge the developing market and entrepreneurship until economies of scale can be achieved for broader scale adoption. Currently, there are 35 U.S. policy programs that provide financial incentives for biochar production, including loans, non-financial policy support, and research and development funding (Pourhashem et al., 2019), such as The Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program that provides loan guarantees of up to 80% of project costs or $250 million (USDA-RD, 2015). The Biomass Crop Assistance Program (BCAP), created by the 2008 Farm Bill and reauthorized with adjustments by the

2014 Farm Bill (U.S. Farm Bill, 2008, 2014), also encourages biochar production. Although BCAP does not directly identify biochar, it offers funds to producers to sustain, harvest, and transport biomass crops. The Natural Resources Conservation Service (NRCS) in the United States Department of Agriculture (USDA) explicitly mentions biochar as a soil amendment to enhance soil carbon and improve the physical, chemical, and biological properties of the soil (USDA NRCS, 2019). Under this interim conservation practice, farmers in some states, including California, can use financial and technical help for applying biochar to their soils. In sum, there have been a few policies and regulations that explicitly promote using biochar for sustainable agriculture. If efficacy is shown in field trials with biochar produced from orchard biomass in California's Central Valley, we posit that the scale of these projects may quickly expand. In fact, once economic parameters are established as our study aims to do, this may accelerate biochar production and field trials. Hence, a market, and bioeconomy, for biochar produced from orchard waste in California could be created in a stepwise manner.

## 2.4. Materials and Methods

### *2.4.1. Excel-based biochar enterprise budget tool*

As follows is a summary of the itemized biochar production costs and assumptions used to develop the biochar enterprise budget (which can be found here: https://ars.els-cdn.com/content/image/1-s2.0-S0956053X21005031-mmc1.xlsx). These values are incorporated in a baseline budget imputed into the regional economic model and used in a Monte Carlo simulation that considers production uncertainty. The biochar production process includes various stages such as preprocessing, pyrolysis, storage, and transportation. An Excel-based enterprise budget mentioned above accounts for costs associated with each production stage. The enterprise budget costs are specific to the Central Valley, California case study; however, the budget has been developed in a spreadsheet format with different drop-down lists to enable users to make modifications based on different projects elsewhere.

The spreadsheet is divided into two main categories: fixed and variable costs. As shown in Table 2-1, fixed biochar production costs include costs of the mobile pyrolysis unit, preprocessing equipment, pyrolysis setup, transportation, water tank, and storage facility among others. The variable costs include fuel, oil and lubricants, labor, and miscellaneous costs. Data collection for enterprise budget development is mainly based on local retailers, literature, and industry partners. To reduce bias and improbable assumptions, data triangulation was adopted, wherein the chosen prices are compared with other similar biochar production projects. All values are expressed in U.S. Dollars (USD). Capital costs are simply expenses associated with fixed inputs used for biochar production. The truck selected for use is a 2020 Chevrolet Silverado 3500HD with a cost of $62,775 (General Motors, 2020). After considering depreciation, insurance, interest, repairs, taxes, and insurance (DIRTI-5) and annual use over 10 years, the fixed cost of the truck each year equals $11,474.73. Moreover, trailers are essential and suitable for hauling oversized loads. These would be required in biochar production to aid with moving the pyrolysis unit. The price range for trailer and fabrication is $20,000 to $50,000 (Bonander Trailers, 2020).

*Table 2-1 Biochar production enterprise budget baseline, Central Valley, California. All production costs associated with biochar production assume 1 Mg day$^{-1}$ production rate and no stochasticity.*

| Items<br>Fixed Costs | Per Unit Cost, USD | $ Mg-$^{1}$ |
|---|---|---|
| Truck | $62,775 | $46.84 |
| Trailer and fabrication | $30,000 | $25.21 |
| Chainsaw | $1,929.95 | $4.44 |
| Horizontal Grinder | $259,400 | $255.87 |
| Utility Tractor | $113,669 | $126.04 |

|  |  |  |
|---|---|---|
| Mobile Pyrolysis Unit | $250,000 | $202.72 |
| Biochar Bagging Equipment | $47,145.13 | $35.73 |
| Storage Shed | $49,121 | $32.33 |
| Portable Toilet | $1,277.35 | $0.84 |
| Portable Septic Tank | $500 | $0.33 |
| Fees, Permits, and Other Payments |  | $24.34 |
|  | Total fixed costs | $754.68 |
| Variable Costs |  |  |
| Fuel |  |  |
| Truck |  | $1.47 |
| Horizontal Grinder |  | $197.22 |
| Utility Tractor |  | $61.63 |
| Biochar Bagging Equipment |  | $9.86 |
| Chainsaw |  | $4.94 |
| Oil and Lubricants |  |  |
| Chainsaw |  | $1.82 |
| Horizontal Grinder |  | $72.58 |
| Utility Tractor |  | $22.68 |
| Biochar Bagging Equipment |  | $3.63 |
| Labor |  |  |
| Pre-processing |  | $127.84 |
| Operations and Transportation |  | $144.88 |
| Miscellaneous |  |  |
| Biochar Bags |  | $45.79 |
| Waste Disposal |  | $23.42 |
|  | Total variable costs | $717.76 |
| Administration fees |  | $69.72 |
| Total Fixed and Variable Costs |  | $1,542.16 |

A horizontal grinder will be used in case there is a need to grind feedstock into a smaller size. The grinder used in this project is Morbark 2230 horizontal grinder and the price is $259,400 (Alexander Equipment, 2020). The chainsaw and utility tractor are important machinery required for feedstock preprocessing. The John Deere 5125R utility tractor and 540R loader are valued at $102,818 and $9,862 (Deere and Company, 2020). We chose the Frontier AP12F Fixed Pallet Forks, valued at $989 (Mutton Power Equipment, 2020) because it is compatible with John Deere tractors. The MAGNUM® 25-inch bar MS 880 chainsaw, valued at $1,929.95, was selected for processing tree logs (Winton Hardware, 2020). The cost of the pilot mobile pyrolysis unit ranges from $250,000 to $300,000, comprising the largest equipment cost in the budget. Biochar will be bagged after production by the Rotochopper Go-Bagger 250, valued at $47,145.13 (Rotochopper Inc, 2020). Until there is sufficient biochar demand that would allow transportation by truckload, bagging biochar is a conservative strategy to cultivate multiple distribution channels. This cost may eventually be eliminated once markets develop. Given that pyrolysis would be conducted with a mobile unit, supplemental facilities for both workers and biochar management are recommended. These include a storage shed, portable toilet, and portable septic tank. The storage shed is required to store biochar between pro- duction and sale. The total cost for these items equals $50,898.35 (All Safety Products, 2020a, 2020b; Buildings Guide, 2019). All businesses must obtain a business license before carrying out business transactions. The estimated range for a California Business License Fee is $50 to$100 for a small business license (Corporation Service Company, 2020), with a $100 business license fee selected for this project. Businesses with employees must maintain workers' compensation insurance coverage on either a self-insured basis, through a commercial carrier, or the state workers' compensation insurance fund. The average cost equals $7.71 of $100 per employee (or 7.71% of payroll). Additional fees for water and sewage come from the City of Chowchilla in the Central Valley (Chowchilla, 2020). Water and sewage cost $47.82 and $19.02 per month, assumed as constant rates throughout the life of the project. Operating costs consist of fuel, oil, and lubricant costs for all the machinery. Fuel costs include diesel and gasoline costs. The costs and consumption vary greatly based on project needs. The baseline cost is calculated based on the assumed distance traveled each day and fuel consumption. The range value for diesel is within \$0.79–\$1.03 $L^{-1}$. For gasoline, the range is \$0.69–\$1.05 $L^{-1}$ (U.S. Energy Information Administration, 2021).

To estimate the diesel consumption for the horizontal grinder, utility tractor, and biochar bagger, we multiplied the liter-per-hour fuel consumption rate by fuel price per liter (Brinker et al., 2002). Based on the literature, we assume hourly fuel consumption in liters for each diesel machine is 0.19 multiplied by kilowatts of each type of equipment (Miyata, 1980).

The horizontal grinder, utility tractor, and biochar bagger have 298.3, 93.2, and 14.9-kilowatt engines. Labor operation costs are estimated at a rate of one person for pre-processing and one person for operations and transportation. The hourly salary range for agricultural machinery operators in California equals $15 to $20 (CalCareers, 2020).

### *2.4.2. Stochastic cost estimation and sensitivity analysis*

Biochar production with a mobile pyrolysis unit is a relatively new technology, with numerous production costs that may not be easily estimated. Most studies use deterministic cost estimation methods based on assumptions and available data (Ahmed et al., 2016; Kim et al., 2015), though this potentially neglects the inherent uncertainty of different biochar production pathways. Due to limited data on mobile pyrolysis units, some budget items were made stochastic to test the net effect on production costs. Probabilistic modeling and stochastic analysis are among the techniques that help to rigorously reduce epistemic uncertainty arising from the lack of empirical data.

To develop a realistic estimation of the biochar production costs and evaluate the effect of uncertainty, a Monte Carlo (MC) simulation is used to capture changes in input values on final estimated biochar costs. The MC technique iteratively estimates the production output given a set of deterministic and random inputs. The MC simulation samples from a designated probability distribution at the start of each iteration and performs forward modeling to generate an output distribution. Input distributions are defined with the help of historical project information and are expected to fit the available data (Connor & MacDonell, 2005).

The max, mean, and min biochar production costs are calculated through a stochastic analysis using @Risk software from Palisade Corporation (Palisade, 2019). The MC simulation uses the following steps:

1. Select the parameters assumed to be stochastic.

2. Based on the literature and available information, develop an appropriate distribution for each parameter using a triangular and PERT distribution, assuming min, mode, and max values, if known.

3. Form a forward model. The forward model assumes all the values are deterministic and estimates the output of a mapping given a specific set of inputs. The forward model in this study comes from the enterprise budget described in Section 2.4.1.

4. Once a distribution for each stochastic parameter and the forward model are developed, the MC iterates over randomly chosen values for each parameter from the corresponding distribution and performs a forward analysis.

5. After 1000 iterations are performed, for each iteration, one value for uncertain parameters are chosen from the corresponding distributions. Using the developed enterprise budget, for each given value and the rest of the values that are already determined (deterministic values), final costs are calculated.

6. Finally, the ensemble of final costs from each iteration is plotted to generate a distribution of the final cost.

A sensitivity analysis is also performed for each case to determine the most sensitive parameters affecting the total cost of biochar production. The effect of a per unit increases in fuel, permit, labor costs, and pro- duction rates on final production costs are evaluated.

### 2.4.3. Break-even analysis

Break-even price analysis informs producers of the price necessary to attain profitability given a particular output, which helps with marketing decisions (Dillon, 1993). We conduct a break-even price analysis of production and sales output needed for biochar producers to recover their costs. Eq (2-1) shows the basic formula for break-even analysis. The Break-Even Point (BEP) is the tons of biochar sold at which the business covers all its costs and does not make a profit or incur a loss. By using this formula, we can assess the minimum level of sales required to cover all costs and avoid losses.

$$Break - Even\ Point\ (Units) = \frac{Fixed\ Costs}{Revenue\ per\ Unit - Variable\ Cost\ per\ Unit} \tag{2-1}$$

### 2.4.4. Regional economic impacts of biochar production

Direct, indirect, and induced economic impacts of biochar production in a 9-county region of California's Central Valley are estimated using IMPAN software (IMPLAN, 2022), an input-output model originally developed by the U.S. Forest Service (Olson & Lindall, 1996; Steinback, 1999) that considers inflationary or deflationary effects over time (Joshi et al., 2012). Regional economic impacts are estimated based on the upper and lower bounds of the 90% confidence interval for $Mg^{-1}$ total cost estimates and four ranges of biochar production rates. Cost estimates from our baseline analysis are entered into the input-output model, rather than commercial revenues, to demonstrate the potential economic contribution of just adding the cost of biochar production as an alternative to burning orchard crop residues. That is, spending on biochar production will create ripples of value through the local economy, whereas burning contributes nothing. The full value of biochar in a future analysis (beyond the scope of this chapter) would include sales that have yet to be developed, health benefits through reduced air pollution, and reduced carbon emissions that have not yet been counted.

## 2.5. Results and Discussion

Table 2-1 shows a summary of fixed and variable biochar production costs for the baseline scenario, equal to \$754.68 and \$717.76 $\mathrm{Mg}^{-1}$ of biochar. These costs are calculated without considering the uncertainty, or stochasticity, in parameters. Capital costs, which mainly include machinery costs, will not change with biochar production volume. In this project, it is assumed that all the machines will be financed for ten years with an interest rate of 10%. Insurance is calculated at 1% of the purchase price and taxes at 8.25% of the purchase price. Variable costs are mostly fuel and labor expenses that directly change with the amount of biochar production. We assume 8 h $\mathrm{day}^{-1}$ work for transportation and operation for 261 days a year. The preprocessing machines run for 4 h $\mathrm{day}^{-1}$. While biomass residues are assumed to be available from nearby farms free of charge, we include feedstock transportation costs in the budget. For the baseline scenario, it is assumed that the biochar production rate is 1 Mg $\mathrm{day}^{-1}$ (Wrobel-Tobiszewska et al., 2015).

### *2.5.1. Stochastic analysis*

The assumptions made in the biochar enterprise budget are subject to change under different circumstances. Fuel prices fluctuate based on changes in demand or supply. Permit costs also vary depending on the location of the project and existing policies. Moreover, investigation and preparation fees cannot be accurately specified before the start of the project. Labor cost is another important variable that can change by season, workload, and operation type. To account for these uncertainties, we analyze labor costs stochastically using a triangular distribution in @RISK software (Palisade, 2019). A triangular distribution has three parameters: the lower limit, the upper limit, and the mean. PERT distributions are considered a simplistic approach to turning the decision-maker's viewpoints into parameter estimates (Stein & Keblis, 2009). The minimum, maximum, and most likely values for each parameter, summarized in Table 2-2, are based on historical data, expert opinions, literature, and project input from experimental biochar production based on different production conditions such as feedstock type and pyrolysis unit properties. Kim et al. (2015) show that the productivity of their BSI pyrolysis system, which was used to produce biochar from sawmill residues, was 0.156 tons per hour. With an average of 7.6 h of work day$^{-1}$, the mean biochar production amount was 1.19 Mg day$^{-1}$. Another biochar economic analysis estimated the CharMaker MPP20 mobile pyrolysis plant could produce 1 Mg of biochar after 4 h of operation (Wrobel-Tobiszewska et al., 2015). Keske et al. (2018) assumed approximately 2 Mg day$^{-1}$ of the operation of biochar could be produced from a mobile pyrolysis unit. Thengane et al. (2020) used a mobile in-wood torrefaction of forest residues to produce biochar and suggested that biochar yield can vary based on the air-biomass ratio and the residence time.

*Table 2-2 Minimum, maximum, and most likely values for each uncertain parameter to form a triangular distribution.*

| **Triangular distribution parameters** | **\$ Mg-$^{1}$ produced biochar** | **Source** |
|---|---|---|
| Permits | Min= \$1.39, Mean=\$13.67, Max=\$29.59 | Chowchilla 2020), (Governor's Office of Business and Economic Development 2020), (Keske et al. 2018) |

| | | |
|---|---|---|
| Fuel | Min= \$13.31, Mean=\$83.33, Max=\$148.29 | (U.S. Energy Information Administration, 2021), (U.S. Department of Energy, 2020), (Brinker et al., 2002), (Miyata, 1980) |
| Labor | Min= \$31.37, Mean=\$103.34, Max=\$197.6 | (CalCareers, 2020), (Keske et al. 2018) |

The mobile pyrolysis unit selected for our project is reported as a batch unit with a capacity of 16 cubic yards. However, based on the availability and type of feedstock and the time of production (winter or summer) the amount of biochar produced can be as low as 0.5 Mg day$^{-1}$. The best-case experimental scenario for our pilot biochar production can be as high as 3.5 Mg day$^{-1}$. To account for all the different production volumes, we consider a PERT distribution for this parameter instead of triangular distribution. A PERT distribution gives more weight to the mean value rather than maximum and minimum values (Petter & Tyner, 2014). The defined PERT distribution for biochar production rate per day is shown in Figure 2-1(d). The values for defining max, mode, and min for a PERT distribution are presented in Table 2-3. The most cited value is approximately 1 Mg day$^{-1}$, therefore the mode set for PERT distribution equals 1 Mg day$^{-1}$. The max and min are defined based on our experimental pyrolysis unit, 0.5 and 3.5 Mg day$^{-1}$.

*Table 2-3 Minimum, maximum, and mode values for production rate to define the PERT distribution.*

| **Mean biochar rate (Mg day$^{-1}$)$^{*}$** | **Description** | **Source** |
|---|---|---|
| 1.19 | BSI pyrolysis system | Kim et al. (2015) |
| 1 | CharMaker MPP20 mobile pyrolysis | Wrobel-Tobiszewska et al. (2015) |
| 2 | CharMaker MPP20 mobile pyrolysis plant (slow pyrolysis) | Keske et al. (2018) |
| 1.56 | Biochar Solutions mobile pyrolysis plant (slow pyrolysis) | Keske et al. (2018) |
| 0.6 | Biochar from woodchips using an integrated portable system | Eggink et al. (2018) |
| 0.5-3.5 | Pilot portable biochar unit | Experimental |

$^{*}$ Assuming a rate of 6 to 8 hours work day$^{-1}$

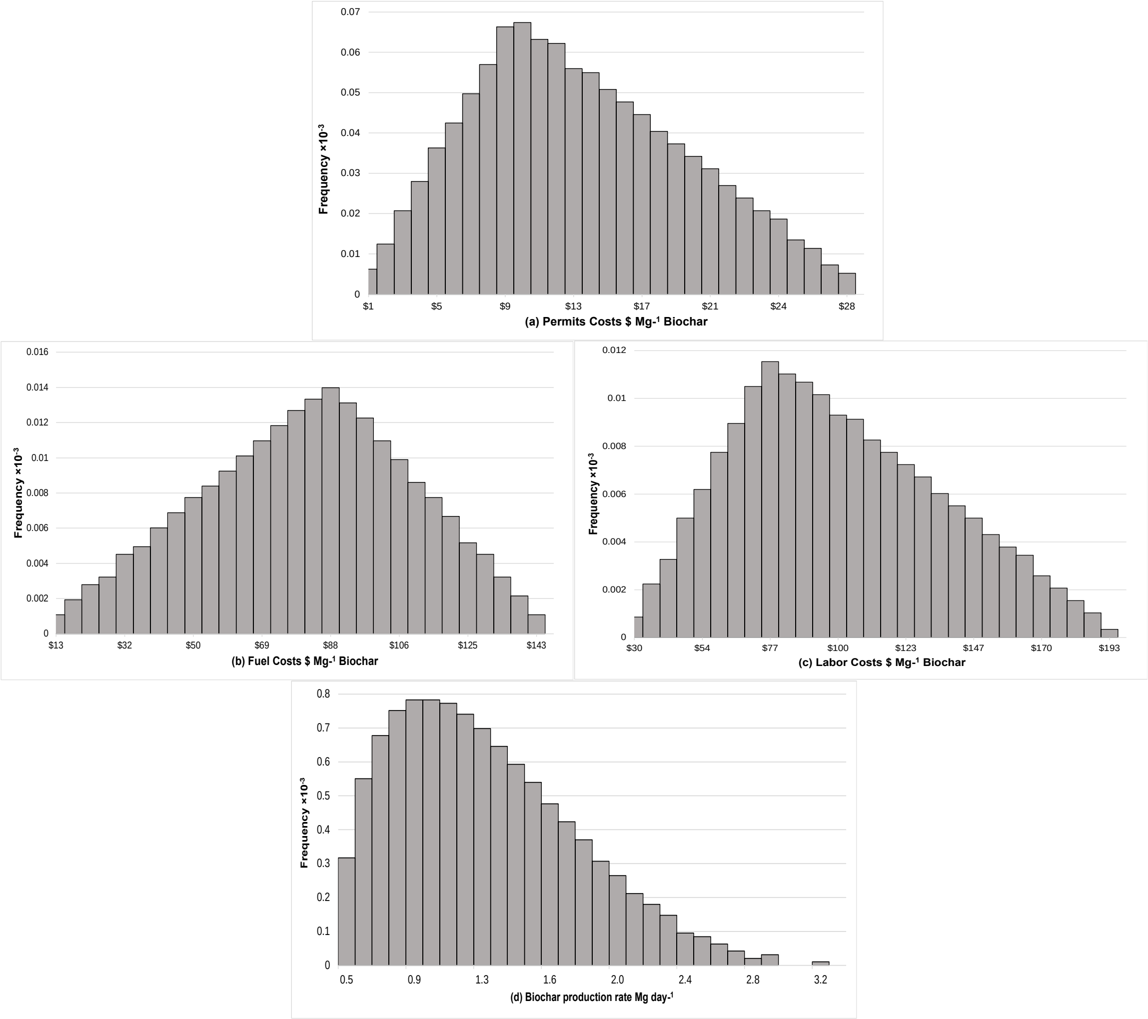

*Figure 2-1 Probability distributions for uncertain inputs. Graphs a, b, and c show the triangular distribution defined for each of the uncertain parameters (permit, fuel, and labor costs). Graph d utilizes a PERT distribution.*

The resulting probability distribution of total biochar cost is presented in Fig. 2-2. This has been simulated from biochar production prices found in the literature and summarized in Table 2-4.

*Table 2-4 Biochar Prices Reported in Literature*

| **Biochar Price** Mg$^{-1}$ | **Description** | **Source** |
|---|---|---|

| | | |
|---|---|---|
| $1044 | Minimum selling price of biochar | (Sahoo et al., 2019) |
| $220-$280 | Break-even prices | (Shabangu et al., 2014) |
| $1600 | Most commonly cited sale prices | (Groot et al., 2018) |
| $1742-$2,077 | Mobile pyrolysis break-even price | (Granatstein et al., 2009) |
| $899–$2778 (mean $1834) | Reported industry wholesale price | (Campbell et al., 2018) |

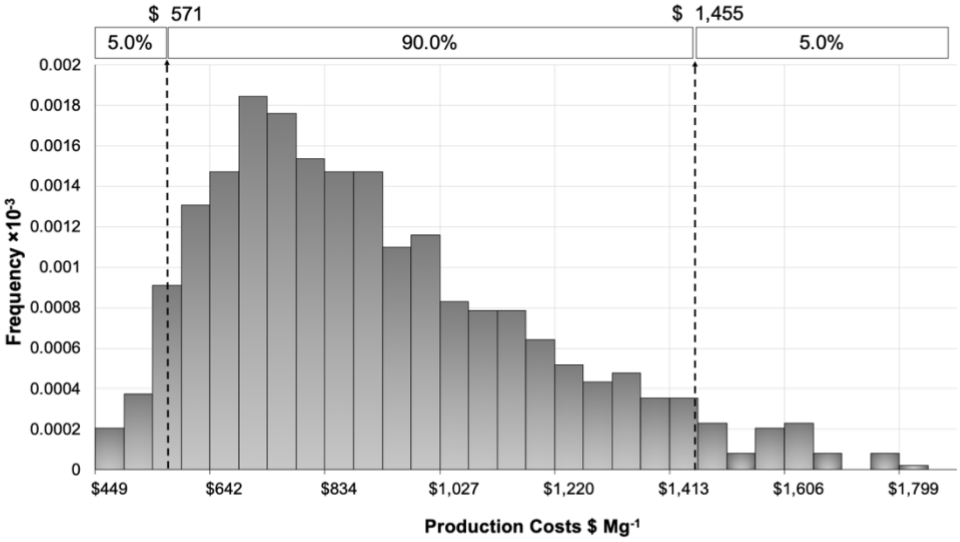

*Figure 2-2 Probability density histogram for total biochar cost per metric ton over production volume and permits, fuel, and labor costs*

The simulation results show that the production costs of using a portable pyrolysis biochar unit range between $448.78 and $1,846.96 $\text{Mg}^{-1}$ of biochar. The cost distribution is not symmetric and is skewed toward the lower limit. This shows that although the upper range is high, the most frequent costs are less than $1,000 $\text{Mg}^{-1}$ of biochar and there is a 90% probability that biochar cost will be between $571 and $1,455 $\text{Mg}^{-1}$. The cumulative probabilities and low, mean, and high values of predicted biochar production costs are presented in Fig. 2-3. There is a less than 5% probability of biochar costs being less than \$570. However, 50% of the result of the simulations indicate a final cost of less than \$863 Mg$^{-1}$.

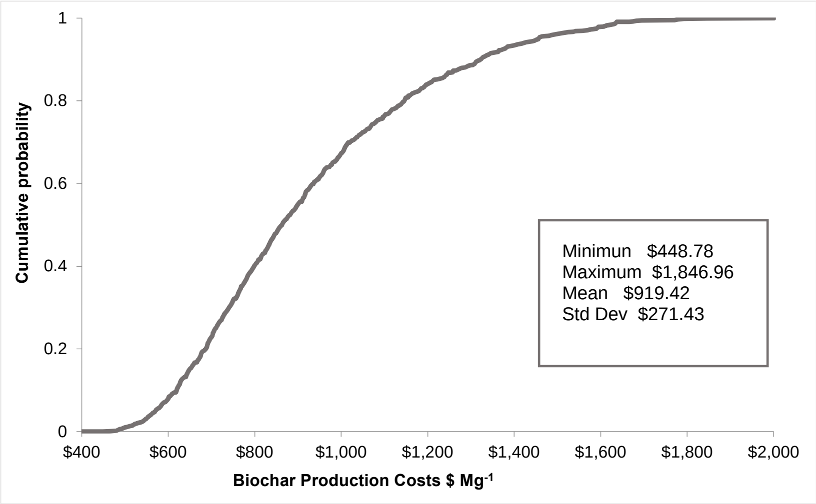

*Figure 2-3 Cumulative density function showing total biochar cost t-1 over production volume, permit, fuel, and labor costs.*

### 2.5.2. Sensitivity analysis

We conduct a sensitivity analysis to measure the sensitivity of final production costs to uncertain inputs (fuel, permit, labor costs, and production rate). The results of sensitivity analysis in Fig. 2-4 show the changes in the mean cost of biochar Mg$^{-1}$ as each uncertain input varies over its range. For instance, when the biochar production rate varies, keeping all other values constant, the mean biochar cost Mg$^{-1}$ is between \$577.88 and \$1,477.56. Similarly, for other parameters, the lower and upper range of the mean biochar cost Mg$^{-1}$ is shown in Fig. 2-4. The bars are shown in decreasing order of their lengths from top to bottom so that the inputs at the top are those with the largest effect on the mean production cost of biochar. The biochar production rate has the most impact on the final cost. By increasing the production volume, we can significantly lower the final cost of biochar. However, it may not be a feasible option unless the technology barriers of high-capacity portable units are resolved and there is a substantial demand for biochar. Other parameters that may affect the costs are labor and fuel expenses. In this study, we assumed that feedstock would be collected free of charge. However, tipping fees would be charged to cover transportation and preprocessing costs.

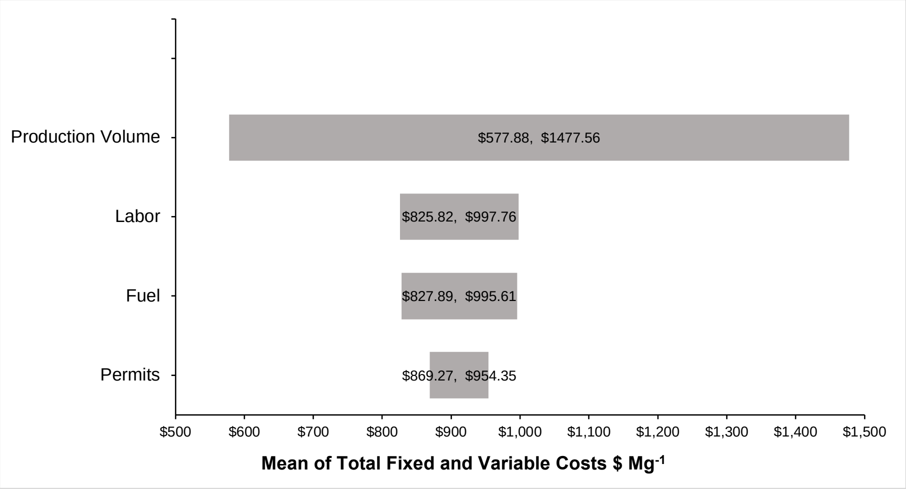

*Figure 2-4 Effect of changes in permits, fuel, labor costs, and production volume on the mean cost of biochar. The numbers in each bar show the lower and upper range of the mean biochar cost Mg$^{-1}$.*

### *2.5.3. Break-even analysis*

Assuming a selling price of $1000 Mg$^{-1}$, conducting a break-even analysis for baseline scenario gives a minimum volume of 655.1 Mg year$^{-1}$. The results are shown in Table 2-5.

Table 2-5 Break-even analysis for baseline scenario assuming a selling price of $1000 Mg$^{-1}$

| | | |
|---|---|---|
| Variable Cost | $718 | per one ton |
| Selling price | $1,000 | per one ton |
| Fixed Cost | $184,896 | annual cost |

| | | |
|---|---|---|
| BEP | 655.1 | tons per year |

Moreover, break-even analysis for the baseline scenario for one year assuming a midline production rate based upon Wrobel-Tobiszewska et al. (2015) of 1 Mg day$^{-1}$ (261 Mg year$^{-1}$) biochar, shows that biochar prices cannot be less than $ 1,426.2 Mg$^{-1}$; otherwise, economic loss occurs. Not surprisingly, when production increases, break-even prices lower. Break-even prices for 2, and 3.5 Mg day$^{-1}$ biochar production equal $1,071.96 and $920.16. These values, even with higher rates of biochar productivity rates, are substantially greater than the break-even prices reported by Shabangu et al. (2014), but on par with mobile pyrolysis break-even prices reported by Granatstein et al. (2009). However, the results of our break-even analysis show that profitability is feasible, with the typical biochar sales price reported by Groot et al. (2018). With some investment into biochar production, it follows that improvement in production efficiency, and market prices would be expected.

### *2.5.4. Regional economic impacts of biochar production by counties in Central Valley*

Expenditure data from the upper and lower boundaries of the 90% cost intervals ($571 Mg day $^{-1}$ and $1,455 Mg day$^{-1}$) were derived in the stochastic analysis presented in Section 2.4.2. These costs, along with four different biochar production levels (0.5, 1, 2, and 3.5 Mg day$^{-1}$) summarized in Table 2-3, were entered into the IMPLAN along with the budget code categories provided in Section 2.3.1. Estimates of regional economic impacts from biochar production in 9 Central Valley counties responsible for most of the state’s almond production are shown in Table 2-6.

*Table 2-6 Regional Economic Impacts of Biochar Production in Central Valley, California.*

| (1) Combination | (2) Activity | (3) Direct Impacts | (4) Indirect Impacts | (5) Induced Impacts | (6) Total Impacts | (7) Total SAM Multiplier |
|---|---|---|---|---|---|---|
| $\$571\text{Mg}^{-1}$ and production rate of 0.5 Mg day$^{-1}$ | | | | | | |
| | Employment | 18.00 | 10.64 | 3.62 | 32.26 | 1.92 |
| | Labor income ($) | 645,015.32 | 535,010.16 | 172,580.33 | 1,352,605.80 | 2.10 |
| | Total value added ($) | 828,737.25 | 795,837.16 | 340,098.43 | 1,964,672.84 | 2.37 |
| | Output ($) | 670,639.50 | 1,602,814.75 | 563,071.55 | 2,836,525.80 | 4.22 |
| $\$571\text{Mg}^{-1}$ and production rate of 1.0 Mg day$^{-1}$ | | | | | | |
| | Employment | 18.00 | 12.40 | 4.04 | 34.44 | 1.91 |
| | Labor income ($) | 688,686.63 | 619,248.24 | 192,429.54 | 1,500,364.41 | 2.18 |
| | Total value added ($) | 1,056,130.50 | 917,278.85 | 379,328.31 | 2,352,737.66 | 2.23 |
| | Output ($) | 1,341,279.00 | 1,848,426.33 | 628,005.81 | 3,817,711.13 | 2.85 |
| $\$571\text{Mg}^{-1}$ and production rate of 2.0 Mg day$^{-1}$ | | | | | | |
| | Employment | 18.00 | 15.92 | 4.88 | 38.80 | 2.16 |
| | Labor income ($) | 776,029.26 | 787,724.40 | 232,127.96 | 1,795,881.62 | 2.31 |
| | Total value added ($) | 1,510,917.01 | 1,160,162.23 | 457,788.06 | 3,128,867.30 | 2.07 |
| | Output ($) | 2,682,558.00 | 2,339,649.48 | 757,874.31 | 5,780,081.79 | 2.15 |
| $\$571\text{ Mg}^{-1}$ and production rate of 3.5 Mgday$^{-1}$ | | | | | | |
| | Employment | 18.00 | 21.20 | 6.14 | 45.33 | 2.52 |
| | Labor income ($) | 907,043.21 | 1,040.438.64 | 291,675.59 | 2,239,157.44 | 2.47 |
| | Total value added ($) | 2,193,096.76 | 1,524,487.31 | 575,477.69 | 4,293,061.76 | 1.96 |
| | Output ($) | 4,694,476.50 | 3,076,484.22 | 952,677.06 | 8,723,637.78 | 1.86 |
| $\$1,455\text{ Mg}^{-1}$ and | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| production rate of 0.5 Mg day$^{-1}$ | | | | | | |
| | Employment | 18.00 | 13.36 | 4.27 | 35.63 | 1.98 |
| | Labor income ($) | 712,625.55 | 665,424.28 | 203,310.10 | 1,581,359.93 | 2.22 |
| | Total value added ($) | 1,180,778.64 | 983,848.46 | 400,832.60 | 2,565,459.71 | 2.17 |
| | Output ($) | 1,708,897.50 | 1,983,061.05 | 663,600.24 | 4,355,558.78 | 2.55 |
| $\$1,455\text{Mg}^{-1}$ and production rate of 1.0 Mg day$^{-1}$ | | | | | | |
| | Employment | 18.00 | 17.85 | 5.34 | 41.19 | 2.29 |
| | Labor income ($) | 823,907.10 | 880,076.48 | 253,889.09 | 1,957,872.67 | 2.38 |
| | Total value added ($) | 1,760,213.29 | 1,293,301.46 | 500,796.65 | 3,554,311.39 | 2.02 |
| | Output ($) | 3,417,795.00 | 2,608,918.92 | 829,063.17 | 6,855,777.09 | 2.01 |
| $\$1,455\text{Mg}^{-1}$ and production rate of 2.0 Mgday$^{-1}$ | | | | | | |
| | Employment | 18.00 | 26.82 | 7.47 | 52.29 | 2.91 |
| | Labor income ($) | 1,046,470.20 | 1,309,380.89 | 355,047.06 | 2,710,898.14 | 2.59 |
| | Total value added ($) | 2,919,082.57 | 1,912,207.45 | 700,724.75 | 5,532,014.77 | 1.90 |
| | Output ($) | 6,835,590.00 | 3,860,634.66 | 1,159,989.04 | 11,856,213.70 | 1.73 |
| $\$1,455\text{Mg}^{-1}$ and production rate of 3.5 Mg day$^{-1}$ | | | | | | |
| | Employment | 18.00 | 40.28 | 10.68 | 68.95 | 3.83 |
| | Labor income ($) | 1,380,314.84 | 1,953,337.49 | 506,784.02 | 3,840,436.35 | 2.78 |
| | Total value added ($) | 4,657,386.50 | 2,840,566.44 | 1,000,616.89 | 8,498,569.84 | 1.82 |
| | Output ($) | 11,962,282.5 | 5,738,208.28 | 1,656,377.85 | 19,356,868.63 | 1.62 |

Not surprisingly, new job creation (18) and direct impacts, calculated as changes that occur in the relevant industry from overall final demand changes (Schmit et al., 2013), both increase when there is simply private and public investment into biochar production. Naturally, total economic output rises with higher production rates and cost levels ($670,639.50 at the lowest cost and production rate to $11,962,282.50 at the highest production and cost rates). The Social Accounting Matrix (SAM) multipliers – computed as a ratio of total impacts to direct impacts, are all greater than one suggesting that a unit dollar worth of investing in the biochar industry would result in more than a dollar value-added economic returns across all economic indicators.

The investment into biochar production as an alternative to crop residue burning also offers increases in indirect impacts (changes in inter-industry purchases in response to new demands from the directly affected industries) and induced impacts, the sales, income, and employment values resulting from expenditures by workers from direct and indirect sectors (Steinback, 1999). The induced (ripple effect) impacts emanate from different economic sectors mainly due to changes in household spending patterns (Miller & Blair, 2009; Perez-Verdin et al., 2008).

The indirect and induced expenditures indicate clear economic benefits in addition to the direct economic expenditures into biochar production. In other words, producing biochar as a management alternative to openly burning orchard crop residues creates additional economic development in the 9-county study region that is also considered an underserved area of the state.

#### *2.5.5. An economic opportunity to create a bioeconomy*

This chapter reviews the costs of biochar production but doesn't address the hard-to-define benefits such as sales revenue, health, or carbon sequestration. A farmer might consider biochar production as adding a cost to their farm, and it would be. Our analysis and previous study findings cannot assure farmers or biochar producers that they would be able to sell their product at a profit. However, as with any new technology, we expect costs will decline and markets will expand, eventually making biochar a profitable venture. In addition, society has a stake in the success of this market in that air pollution will be reduced and carbon will be sequestered. While the value of reducing air pollution is unknown, there is a pecuniary benefit generated by biochar production that might justify a social investment to help farmers kickstart this market. A case could be made for underwriting a biochar production program for farmers on a pilot basis as an alternative to crop residue burning. The costs to adopt biochar are shown as the direct cost of output in Table 2-5. For example, for the \$1,455 $Mg^{-1}$ scenario, at a conservative 0.5 Mg $day^{-1}$ production rate, the cost for farmers to adopt biochar would be about \$1.71 million. This investment by farmers ripples through the economy, generating indirect and induced returns. The value-added generated by their investment is about \$2.57 million. Therefore, subsidizing the full cost of \$1.71 million for farmers to invest in biochar would generate about \$2.57 million in value-added. The pecuniary gains (\$2.57 million – \$1.71 million) are positive. This justifies the financial investment, at least in the short run. Additional benefits will accrue through reduced pollution and carbon emissions. Said differently for clarity, if a subsidy was offered, biochar production would cost farmers either nothing or very little depending on the size of the subsidy. The citizens that financed the subsidy would receive net pecuniary gain and would arguably receive more environmental benefits than what they spent on the subsidy. More importantly, investors would start from zero social cost, and receive the benefits biochar has to offer: health, carbon sequestration, and revenue from sales for the biochar producers.

### 2.6. Conclusions

Our goal was to determine how we might turn burning residues in orchards around to create a bioeconomy through biochar production. This chapter delivers a stochastic analysis to reduce epistemic uncertainty arising from highly variable biochar production and nascent commercial sales. However, until crop yield efficacy is clearly demonstrated, it is unlikely that commercial-scale markets will develop. Management of crop residues, and specifically orchard waste, is a complex problem in the study region and across the world. Approximately 50% of crop residues are burned, though converting crop residues to biochar is a sustainable closed-loop approach to accommodate problems associated with waste management. The enterprise budget and the stochastic cost estimations developed for biochar production in this chapter can provide the necessary information to mitigate risks in the biochar production phase both in the U.S. and other countries globally facing a crop residue problem. Our findings confirm our hypothesis that there should be a feasible range of costs for biochar production and these results provide a launch-pad for which biochar production can be feasibly achieved both in California and other countries facing biomass problems. The findings are plausible, and the standard deviation is not so high, which suggests less variability.

In this chapter, we proposed to use the produced biochar as a soil amendment to agricultural fields near the location of biochar production. However, the on-farm benefits, such as the potential to sell biochar so that farmers could increase yields have not been discussed. Admittedly, this is an important limitation of our study and could be an interesting research area for future studies. Most importantly, biochar production from agricultural waste can be an important step toward improving a global bioeconomy. However, larger-scale research is needed to determine possible benefits and address potential social and environmental problems such as air pollution and global climate change.

Given our findings, as in Palansooriya et al. (2019), this study suggests that biochar production can be an economically beneficial endeavor that should be promoted in the Central Valley, California, and indeed globally if a global bioeconomy is to be achieved. At the state level, there is considerable opportunity to expand biochar production as an alternative management practice to crop residue burning. According to Kaffka et al. (2013), California generates at least 70 million tons of waste biomass per year and in 2009, the Central Valley's almonds and walnuts contributed about 199,000 and 496,000 dry tons of biomass waste each year. The authors note the higher value of the production of almonds and walnuts as one of the leading factors toward biomass generation. Once biochar production has gained efficiency, there is considerable room for expansion. California has at least two million acres of trees and vine crops which produce substantial amounts of woody biomass from clipping. Given the potential to expand biochar production, this study is relevant to policymakers across the world as it provides evidence to suggest that biochar production is economically feasible and has the potential to improve most economic indicators. Furthermore, we offer a way to incentivize biochar production through subsidizing costs, while recouping the costs of the subsidies through indirect and induced costs. That is, the farmer spends money on a new production link that creates a bioeconomy, the government offsets those costs with the indirect and induced costs that will fully make up for the cost of the subsidy, and both producers and society get all of the benefits of biochar at no cost and less risk. In other words, biochar can be produced at no net cost, and the net benefit will be positive. Once biochar producers show consistent profitability (with more predictable biochar market prices and biochar output), biochar production would eventually become a private-sector investment.

### 2.7. Acknowledgments

Chapter 2, in full, is a reprint of the material as it appears in Nematian, M., Keske, C., & Ng'ombe, J. N. (2021). A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Management, 135, 467-477. The dissertation author was the primary investigator and author of this paper.

# Chapter 3 Sustaining Agricultural Economies: Regional Economic Impacts of Biochar Production from Waste Orchard Biomass in California's Central Valley

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## 3.1. Abstract

The prominent role of agriculture in greenhouse gas (GHG) emissions has increased global interest in biochar. This carbonaceous biomass product, that has emerging efficacy for GHG emissions reduction. While a growing body of literature indicates positive economic impacts of biomass-related products, scant evidence exists about the potential regional economic impacts of biochar production. Since biochar is a new industry and there is no North American Industry Classification System (NAICS) code for biochar, we modified the available industries in the IMPLAN database to estimate the direct, indirect, and induced economic impacts of six potential biochar pricing and production opportunities in Central Valley, California. Results suggest that depending on the biochar price and conversion rates, biochar would create between 16.56 to 17.69 new full- and part-time jobs per year that would contribute between $1.2 to $5.75 million per year to labor income. Biochar production would add to the Gross Domestic Product (GDP) about $106,295 ($5.2 million) per year with a conversion rate of %15 (%35) and a biochar price of $280 ($2,512) per metric ton. Similarly, biochar’s impacts on gross output would be positive, regardless of the biochar conversion rate and price, which suggests the need for more investment in the sector. We find that all regions would benefit in terms of

employment, labor compensation, value addition, and gross output though Madera County would have the least economic returns. Meanwhile, Fresno County with the most biomass would have the most economic impacts suggesting that policy should be directed at encouraging biomass production and marketing in areas with the most biomass.

## 3.2. Introduction

Agricultural waste management practices, such as open field burning, can emit high levels of greenhouse gas (GHG) like methane ($CH_4$) and nitrous oxide ($N_2O$) (Romasanta et al., 2017). According to the United States Environmental Protection Agency (EPA), the nation's annual $CH_4$ and $N_2O$ emissions increased by a fraction of 14% in 1990 to 16% in 2020 (EPA, 2022). The impact of increasing emissions on climate change and human health prompted the state of California to implement its climate pollutant reduction law (SB 1383) and regulations forbidding the burning of agricultural waste by 2025 (Keske, 2020; Sabalow, 2021). Other nations and large economies across the world are observing how California implements alternative crop residue management techniques without eroding economic development. Burning agricultural residue has historically been the lowest-cost management option for agricultural producers in California and elsewhere (Nematian et al., 2021). However, the negative impacts of GHGs on human health and the environment, particularly for low-income communities (paradoxically dependent upon agriculture as a sole driver of economic activity) are well-documented (Springsteen et al., 2011). To increase the positive economic impacts of agriculture and attenuate adverse environmental and health effects from burning waste biomass, this chapter quantifies regional economic benefits to agriculturally dependent regions in California's Central

Valley from converting waste orchard biomass into biochar using a regional economic analysis for new economic sectors.

California’s Central Valley is one of the most productive agricultural areas in the world. The region has a fraction of 8% of the U.S. agricultural output, and 25% of the nation’s food production, including a high percentage of the nation’s tree nuts and nearly 100% of almonds (Bertoldi, 1989; Faunt et al., 2009). Like many other agriculturally dependent regions, communities in California’s Central Valley struggle with significant socioeconomic and environmental issues, namely high unemployment rates, rural poverty (Hanak et al., 2019), low water security, and poor air quality (August et al., 2021). In the San Joaquin Valley, within the southern Central Valley, more than half of the residents live in disadvantaged communities with insufficient healthcare access (August et al., 2021; Sabalow, 2021) and are disproportionately harmed by air pollution, including respiratory illnesses arising from burning agricultural wastes. This cycle perpetuates health disparities (Becker, 2021).

To jointly address the region's environmental and employment dilemma, we posit that there may be significant financial benefits from converting agricultural wastes into biochar as a value-added product that has shown emerging environmental benefits, including GHG mitigation (Hammond et al., 2011; Roberts et al., 2010). The Intergovernmental Panel on Climate Change (IPCC) notes mitigating global warming requires actions that would significantly reduce GHG emissions (IPCC, 2013). Peters et al. (2015) indicate that perpetual CO2 sequestration may be achieved by applying biochar to soil.

In addition to GHG mitigation, Roberts et al. (2010) and (Hammond et al., 2011) recommend biochar as a soil amendment for increasing soil carbon storage contributing to increased production yields. Additional benefits of biochar as soil amendment include reduced $N_2O$ (IPCC, 2013; Karhu et al., 2011; Peters et al., 2015), $CO_2$, and $CH_4$ emissions (Karhu et al., 2011; Spokas & Reicosky, 2009; Zhang et al., 2012). Other potential benefits include reduced soil bulk density, improved water retention, and reduced leaching of soil nutrients (Laird et al., 2009; Lehmann et al., 2011). Recent studies have shown that adding biochar as a bulking agent to the animal manure composting process may enhance composting process performance while reducing ammonia ($NH_3$), $CH_4$, and $N_2O$ emissions (Akdeniz, 2019; B. P. Harrison et al., 2022; Jia et al., 2015).

The incorporation of biochar as a soil amendment has the potential to enhance the quality of soils contaminated with heavy metals (Tauqeer et al., 2021). Results of studies by Shahbaz et al. (2019) and Turan et al. (2018) show using biochar as a soil amendment to Nickel-rich soils can significantly immobilize Nickel in the soil. This not only leads to substantial improvements in plant height but also results in increased shoot and root dry weight, ultimately culminating in enhanced grain yield (Shahbaz et al. 2019). Furthermore, the combination of biochar with additional immobilizing amendments demonstrates that biochar is an effective strategy for the remediation of Pb-contaminated soils (Naeem et al., 2021; Rasool et al., 2022; Tauqeer et al., 2022) and Cd-polluted soil (Zubair et al., 2021). While the primary objective of this chapter centers on the production of biochar from biomass waste, it is important to recognize the broader spectrum of innovative applications that biomass offers. One such promising avenue lies in the realm of nanocomposites, where the utilization of almond extract can prove to be a game-changer, particularly due to its remarkable antibacterial properties, especially in the context of wastewater remediation (Mahdi et al., 2022; Yousefi et al., 2021).

The above-mentioned benefits fortify the call for increased agricultural biochar production (Laird et al., 2009; Larson, 2008; Sohi et al., 2010) across the world, especially in areas with abundant biomass availability like the United States. Cherubin et al. (2018) rank the U.S. as the second-largest biomass producer in the world, accounting for 29% of biomass availability.

Though work has been done on the potential economic benefits of biochar-related products (Ahmed et al., 2016; Dickinson et al., 2015; Field et al., 2013; Keske et al., 2019; Lee et al., 2020; Mohammadi et al., 2017; Nematian et al., 2021), the impact of biochar on regional economic development has not been closely examined, in part due to the newness of the economic sector with heterogeneous biomass quality and high price variability. If regional economic benefits can be quantified for at least one prominent crop or industry sector in California's Central Valley, we assert that biochar production could be positioned to expand rapidly as California Air Resources Board regulations align to address climate change and air quality. California ranks among the top agricultural-producing states and generates at least 70 million tonnes of waste biomass per year (Breunig et al., 2018). According to Kaffka et al. (2013), California also has at least 8,000 km$^2$ of trees and vine crops that produce substantial amounts of woody biomass from clippings. This suggests that there is a substantial opportunity to expand biochar production as an economic sector. Results of our research may further encourage using biochar as a sustainable alternative to open agricultural burning within California and elsewhere with similar biomass and air quality issues.

In sum, this study estimates the regional economic impacts of converting almond biomass waste to biochar in California's Central Valley as a new economic sector that may generate in employment, labor income, total industry output, and total value added. Though California is poised to phase out burning agricultural wastes by 2025, this chapter documents the positive economic benefits of converting biomass into a soil amendment and the potential to form a new economic sector. We hypothesize that biochar production in six counties located in Central Valley, California can impact the rest of the counties in the State. Therefore, the questions we try to investigate are: (1) how much almond biomass waste is available in each county and needs to be managed? (2) how will biochar production impact the economy at county levels in California?

### 3.3. Related Literature

Few studies examine the economic impacts associated with biochar production because biochar efficacy and impacts are only emerging. (Beesley et al., 2011) contend that biochar's efficacy is unclear due to uncertainty about organic material combinations. Ogbonnaya & Semple (2013) observe that even though animal manure, crop residues, forestry by-products, industrial by-products, urban yard wastes, and sewage sludge can be pyrolyzed to produce biochar, not all organic materials are suitable for producing biochar suitable for agricultural use. They suggest that some feedstock and production combinations may be ineffective in retaining nutrients prone to microbial decay.

Moreover, some studies considered the potential negative environmental impacts of biochar production. Some of these impacts include the release of $CO_2$ during the pyrolysis process, Energy Consumption, Transportation Emission, and Soil Contamination (Xiang et al., 2021). It's important to note that many of these negative environmental impacts can be mitigated through responsible and sustainable biochar production practices, such as using waste biomass, implementing proper emissions controls, and carefully managing feedstock sourcing. Regulations and guidelines for biochar production can also help minimize these negative effects and promote its sustainable use as a valuable tool in addressing environmental challenges (C. Li et al., 2018; Nematian et al., 2021).

Some studies in the United States and elsewhere have been dedicated to evaluating the economic impacts of biomass products, like woody biomass and agricultural wastes, that are generally considered inputs in biochar production (Ahmed et al., 2016; Aksoy et al., 2011; Dickinson et al., 2015; English et al., 2007; Field et al., 2013; Jackson et al., 2018, 2019).

Other studies specifically focus on the economics of biochar (Brown et al., 2011; Galinato et al., 2011; Shabangu et al., 2014; Shackley et al., 2011). We briefly overview how previous economic studies have influenced the methods selected for this research. Jackson et al. (2018) demonstrate increased economic development by introducing woody biomass processing (WBP) into a rural area in Central Appalachia, using an input-output framework to assess WBP under three different pathways, fast pyrolysis, ethanol, and coal-biomass to liquids. He et al. (2016) use an IMPLAN input-output regional economic analysis model to determine the supply and economic impacts of harvesting regional woody biomass in the southern United States, concluding that when merchantable round wood is harvested as woody biomass, some states benefit more than others. Timmons et al. (2007) estimate economic impacts associated with the construction of newly built biomass energy facilities in Massachusetts and compare these to business-as-usual scenarios constructed elsewhere. A study by Aksoy et al. (2011) investigates allocation, optimum facility location, economic feasibility, and economic impacts of biorefinery technologies for feedstock in Alabama. Using IMPLAN modeling, Aksoy et al. (2011) find comparable economic impacts among the four biorefinery technologies in Alabama.

A study by English et al. (2007) examines the economic impacts of co-firing biomass feedstock with coal in coal-fired plants under three emission credits as well as two cofiring level scenarios in Alabama, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. In their study, the economic impacts were estimated using IMPLAN considering such important activities as production, collection, and transportation of feedstock. Altogether, their findings show inconsistent economic impacts in the trading areas. Michaud & Jolley (2019) determined that the economic contribution of the wood industry in Appalachian Ohio improves investment and value-added opportunities that support economic growth.

## 3.4. Materials and Methods

### *3.4.1. Economic Impact Analysis*

Like previous studies using IMPLAN to model regional economic impacts of biomass production, our study also consists of input-output modeling of direct, indirect, and induced impacts with IMPLAN, though we align the analysis to demonstrate regional economic impacts of biochar production in California's Central Valley as a new industry, through an IMPLAN software feature only recently made available. Direct impacts are defined as the changes that occur in the industry where a final demand change is made while indirect impacts are the changes in inter-industry purchases as they respond to new demands from the directly affected industries (Schmit et al., 2013). Induced impacts represent the sales, income, and employment that result from expenditures by workers from direct and indirect sectors (Steinback, 1999). The summation of direct, indirect, and induced impacts represents total impacts. Even though the direct impacts show immediate changes in the production of economic activity, the indirect impacts show the cumulated impacts from between-industry expenditure’s economy of interest (Joshi et al., 2012; Miller & Blair, 2009; Perez-Verdin et al., 2008). The induced (alias ripple) impacts emanate from different economic sectors mainly due to changes in household spending patterns (Miller & Blair, 2009; Perez-Verdin et al., 2008). In this study, the direct impacts represent the changes in economic activities attributed to the expenditure required for biochar production. The indirect impacts are the changes in economic activities resulting from inter-industry expenditure and the production of biochar. Induced impacts refer to the sales, income, and employment from expenditures by employees of the biochar industry and non-biochar industry due to biochar production enterprise.

Figure 3-1 shows connections between biochar production and economic impacts. Biochar production using a portable unit includes businesses such as transportation, almond farms, and fuel retailer. The cash flows generated by biochar production will increase household incomes which consequently increase household expenditures and income tax revenues. In sum, it helps with recirculating money in the local economy.

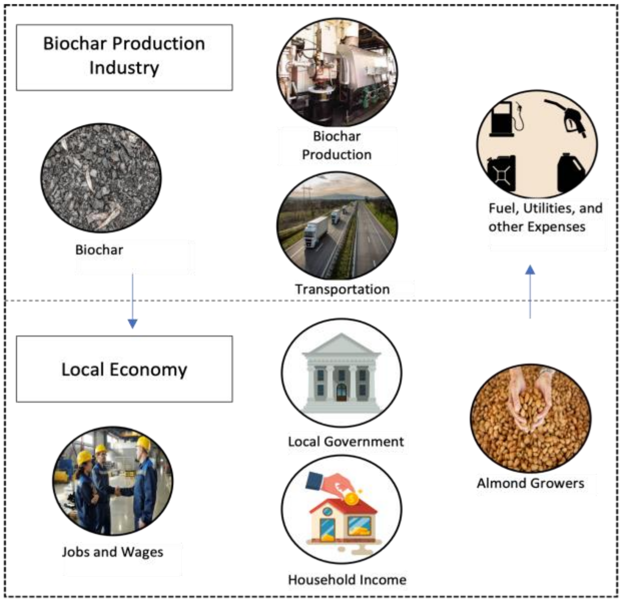

*Figure 3-1 Simplified presentation of the structure and economic impacts of a biochar industry in a local economy*[1]

Historically, regional economic analysis using input-output modeling had been computationally expensive and time-consuming. For example, the need for large primary data on production and consumption functions, trade relationships, and distributional characteristics made regional economic modeling not only complex but also impractical (Propst & Gavrilis, 1987). To cater for this, the U.S. Forest Service developed the IMPLAN modeling system (Olson & Lindall, 1996; Steinback, 1999), a well-developed economic input-output model that is designed to scheme economic impacts produced by a variety of factors at the national, state, regional, and county levels (He et al., 2016). Steinback (1999) suggests that IMPLAN is the most widely used and ready-made tool for regional economic impact analysis among practitioners because of its tremendous flexibility in terms of geographic coverage, model formulation, and ability to integrate user-supplied data during

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[1] Photos used for Figure 3 are obtained from: https://www.istockphoto.com and http://biomassmagazine.com.

analysis. Additionally, Joshi et al. (2012) contend that IMPLAN is flexible in considering inflationary or deflationary effects with time and has outstanding data customization abilities which make it superior to other regional economic impact models.

### *3.4.2. Data Sources*

Our input-output model utilizing the IMPLAN software requires data on (1) annual available almond biomass residue; (2) almond acreage in the studied counties; (3) biomass to biochar conversion rates; (4) biochar production costs and (5) possible biochar selling prices. These data were collected from different sources, as described below.

Six counties with the most almond acreage in the Central Valley, California were selected. The projected almond acreage data was obtained from the 2020 California almond acreage report (USDA NASS, 2021). It is estimated that each year, 80.94 $km^2$ of almond orchards will need to be removed due to age and wind damage. Based on the assumption of 22,239 trees per $km^2$ and 200 kg mass per tree, each $km^2$ of bearing orchard would generate 134,771 kg of biomass annually (Chen et al., 2010). Table 3-1 shows the estimated total biomass available for each county, as well as the output of biochar for different conversation rates.

*Table 3-1 Estimated total almond acreage biomass available for each county and produced biochar for different conversation rates*

| County | 2020 Almond Acreage | Total biomass (Metric ton) | Biochar Output (Metric ton) | | |
|---|---|---|---|---|---|
| | | | 15% | 25% | 35% |
| San Joaquin | 1268 (5.13 $km^2$) | 691.63 | 103.74 | 172.91 | 242.07 |
| Madera | 1034 (4.18 $km^2$) | 564.00 | 84.60 | 141.00 | 197.40 |
| Merced | 1630 (6.60 $km^2$) | 889.08 | 133.36 | 222.27 | 311.18 |
| Stanislaus | 2189 (8.86 $km^2$) | 1193.99 | 179.10 | 298.50 | 417.90 |

| | | | | | |
|---|---|---|---|---|---|
| Kern | 1907 (7.71 km$^2$) | 1040.17 | 156.03 | 260.04 | 364.06 |
| Fresno | 3029 (12.26 km$^2$) | 1652.17 | 247.83 | 413.04 | 578.26 |

In addition to available almond biomass waste, biochar yield measures how much biochar can be produced from a given amount of raw biomass (Sadaka et al., 2014). The average yield is a fraction between 15% to 35% (Thengane et al., 2020). It is important to note that we are discussing orchard biomass in its loose form and to prepare it for biochar production, preprocessing becomes necessary. When dealing with a shell-based feedstock that doesn't contain external particles, preprocessing is usually unnecessary. However, if the feedstock is wood-based, preprocessing is recommended to achieve a uniform shape and ensure a homogeneous final product. Essentially, if your feedstock is already uniform in shape and free from external contaminants, there's generally no need for preprocessing.

Biochar production costs and selling prices vary depending on several factors, such as the type of feedstock used, the production method, and the market conditions. The biochar market is still in its early stages, so we use reported a range of biochar prices from the literature (Campbell et al., 2018; Maroušek et al., 2019), positing that a biochar market is small or does not exist, and market transactions are negligible. The wide range of prices is consistent with the observation of nonstandard biochar pricing across the world. In a techno-economic analysis of solid biofuels and biochar production for Northern California, Sahoo et al. (2019) suggest a minimum biochar selling price of $1,044 per ton. Similarly, (Campbell et al., 2018) examine the effects of fuel price on project financial performance for biochar and find that wholesale biochar price in the United States ranges from $899 to $2,778 per ton. In Shabangu et al. (2014) biomass to biochar and methanol profitability study, breakeven biochar prices differ by pyrolysis temperatures. They found breakeven prices ranging from $220 to $280 per ton when pyrolysis temperatures equal 300 °C and 450 °C, respectively. A survey of biochar prices in the U.S. by Groot et al. (2018) indicates that the most often cited price paid for biochar is $1,600 per ton. Shackley et al. (2011) estimate a breakeven biochar selling price in the UK ranges from $222 to $584 per ton. A summary of these studies indeed shows varying biochar prices. To encompass a wider range of biochar price possibilities, our study considers minimum, mean, and maximum biochar prices of $80, $280, and $2,512 per ton, respectively, to reflect plausible prices upon which biochar could be sold from different regions of the world. This means that our analyses are done assuming potential combinations of minimum, mean, and maximum biochar prices and biochar conversion rates that lead to nine different sets of analyses. The scenarios are shown in Table 3-2.

*Table 3-2 The defined nine scenarios by varying biochar price and conversion rate*

| Scenarios | Biochar Selling Price (USD per metric ton) | Biomass to Biochar Conversion Rate |
|---|---|---|
| 1 | 80 | 15% |
| 2 | 80 | 25% |
| 3 | 80 | 35% |
| 4 | 280 | 15% |
| 5 | 280 | 25% |
| 6 | 280 | 35% |
| 7 | 2512 | 15% |
| 8 | 2512 | 25% |
| 9 | 2512 | 35% |

To estimate biochar production costs, we consider using a mobile system employing torrefaction to produce biochar (Kung et al., 2019). This torrefaction unit is priced at 200,000 USD. This unit is portable and capable of continuous reactions that can run with the capacity of processing 2 t hour$^{-1}$ (Thengane et al., 2020). Other required machinery and equipment include the cost of transportation, workers, and miscellaneous expenses (Nematian et al., 2021). The detailed information about each Commodity Index used is shown in Table 3-3.

*Table 3-3 Explanation of Commodity Indexes used in the IMPLAN model*

| **(1)**<br>**IMPLAN 546 Commodity Index** | **(2)**<br>**Commodity** | **(3)**<br>**Percentage** |
|---|---|---|
| Code 3049 in IMPLAN | Water, sewage, and other systems | 1.2% |
| Code 3047 in IMPLAN | Electricity transmission and distribution | 1.88% |
| Code 3154 in IMPLAN | Refined petroleum products | 10.89% |
| Code 3157 in IMPLAN | Petroleum lubricating oil and grease | 0.04% |
| Code 3393 in IMPLAN | Wholesale services - Professional and commercial equipment and supplies | 0.45% |
| Code 3347 in IMPLAN | Motor vehicle gasoline engines and engine parts | 0.60% |
| Code 3349 in IMPLAN | Motor vehicle transmission and power train parts | 0.69% |
| Code 3294 in IMPLAN | Industrial process furnaces and ovens | 30% |
| Code 3479 in IMPLAN | Waste management and remediation services | 2.10% |
| Code 3455 in IMPLAN | Legal services | 1.05% |
| Code 3444 in IMPLAN | Other insurance | 3.56% |
| Code 3186 in IMPLAN | Plastics packaging materials and unlaminated films and sheets | 15% |
| Code 3060 in IMPLAN | Maintained and repaired nonresidential structures | 2.78% |
| Code 3400 in IMPLAN | Wholesale services - Other nondurable goods merchant wholesalers | 1.00% |
| Code 3416 in IMPLAN | Water transportation services | 0.04% |

| | | |
|---|---|---|
| Code 3417 in IMPLAN | Truck transportation services | 1.88% |
| Code 3428 in IMPLAN | Software publishers | 0.23% |
| Code 3445 in IMPLAN | Insurance agencies, brokerages, and related services | 1.60% |
| Code 3447 in IMPLAN | Other real estate services | 0.80% |
| Code 3456 in IMPLAN | Accounting, tax preparation, bookkeeping, and payroll services | 1.19% |
| Code 3460 in IMPLAN | Computer systems design services | 0.76% |
| Code 3465 in IMPLAN | Advertising, public relations, and related services | 0.19% |
| Code 3468 in IMPLAN | Marketing research and all other miscellaneous professional, scientific, and technical services | 0.81% |
| Code 3514 in IMPLAN | Electronic and precision equipment repair and maintenance | 4.91% |
| Code 3515 in IMPLAN | Commercial and industrial machinery and equipment repair and maintenance | 7.11% |
| Code 3531 in IMPLAN | Other products and services of State Govt enterprises | 0.03% |
| Code 3260 in IMPLAN | Farm machinery and equipment | 8.61% |
| Code 3290 in IMPLAN | Industrial trucks, trailers, and stackers | 0.57% |

### *3.4.3. The IMPLAN model*

Since biochar is a new industry and there is no North American Industry Classification System (NAICS) code for biochar, we modified the available industries in the IMPLAN database (IMPLAN, 2022). We believe that the biochar production process is closest to code 15 (Forestry, forest products, and timber tract production). We start from code 15 and modified the spending patterns to reflect the specific purchases in our proposed biochar project. The steps we followed to build the model are as follows:

1. From the regions tab, we choose six counties (Fresno, Kern, Stanislaus, Merced, Madera, and San Joaquin). Also, with the help of the Region List option, we combine all other counties in California to create grouped geographies to analyze.

2. We define six events using the newest IMPLAN event type: Industry Impact Analysis (Detailed) (Clouse, 2022). The most important parameters that need to be defined are Intermediate Inputs, Employment, and Total Output. For each county, we calculate the intermediate inputs i.e., the goods and services that are used in the production process based on variable and fixed costs of production. Next, we assume that two employees are required for each county to operate the portable biochar production unit (Nematian et al. 2021). Total output is the total production value of an industry, which in our study is the selling price of biochar multiplied by total production volume.

3. Since six counties have the most almond acreage in the Central Valley, California (USDA NASS, 2021), we assume that biochar production will happen in the six counties (i.e., Fresno, Kern, Stanislaus, Merced, Madera, and San Joaquin). Therefore, each event will be assigned to the corresponding county (group) where we will convert almond residues to biochar. With the help of Multi-Regional Input-Output (MRIO) analysis, we are able to see how impacts in one county disperse into other regions.

## 3.5. Results and Discussion

### *3.5.1. Economic Impacts of Biochar Production in Central Valley, California*

The results of our study can be divided into three main impacts. Overall impacts, specific impacts, and impacts of six biochar production counties in all other counties. Figure 3-2 illustrates the six counties within which biochar production takes place, each marked as a distinct region, and the corresponding events associated with biochar production utilizing available biomass resources. For instance, in Region A (Fresno County) we have one Event (biochar production facility) which initiates Direct Effects within Region A. These Direct Effects within Region A subsequently led to the emergence of Indirect and Induced Effects across all other regions. Utilizing Multi-Regional Input-Output (MRIO) analysis, we have the capacity to model events that span multiple regions. Notably, as depicted in level two of the hierarchy in Figure 3-2, even in regions where biochar production does not occur, we can observe the presence of Indirect and Induced Effects.

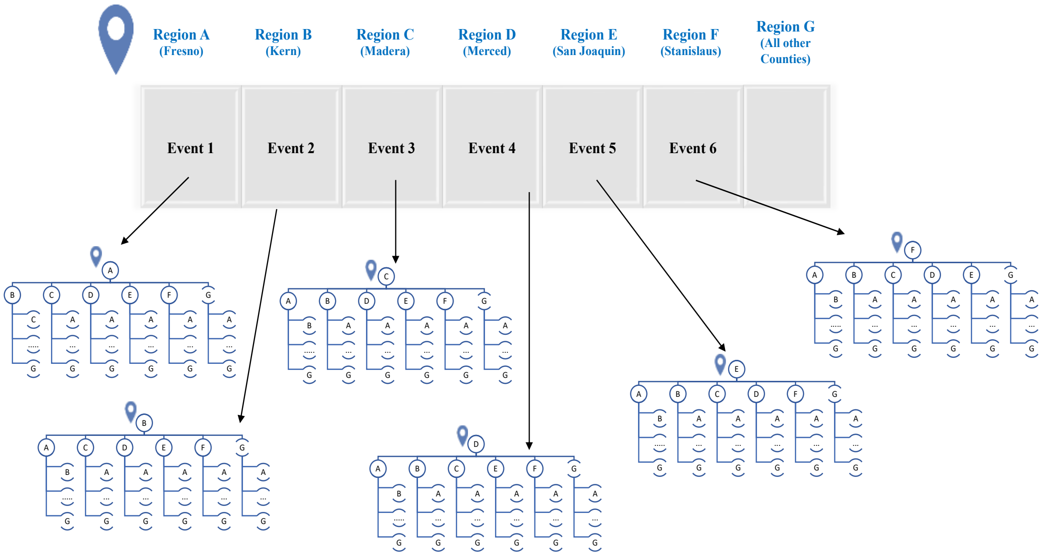

*Figure 3-2 Direct, Indirect, and Induced Impacts of biochar production. Each region except region G will have a specific event (biochar production).*

Results reported in Table 3-4 are the potential economic impacts of biochar production in six counties in California's Central Valley. These results encompass the cumulative impacts stemming from all production facilities within the specified regions. The data is organized based on our defined scenarios, combining biochar prices and conversion rates. Results from our analysis indicate that, in a scenario where the price of biochar is set at $80 per ton and a conversion rate of 15% is applied, there is a promising economic outlook for the local economy. This biochar production activity is projected to create a total of 12 full- and part-time employment opportunities, constituting the average annual employment figures. This job creation has the potential to significantly impact the labor market within the region. Moreover, the economic benefits extend beyond employment generation. The direct gross output associated with this biochar production activity is estimated to be approximately $73,000. This signifies the economic value generated directly from the production process, including revenues from biochar sales and associated activities. However, the positive economic effects of biochar production do not stop there. The ripple effects of this activity are expected to be felt across the regional economy. Specifically, it is anticipated that this biochar production activity will indirectly create an additional 4 full- and part-time jobs. These jobs emerge as a result of the interconnected supply chain and economic activities stimulated by the initial production process. This highlights the intricate web of economic relationships within the region, where one industry's growth can catalyze expansion in related sectors.

*Table 3-4 Total economic impacts of biochar production in six counties (Fresno, Kern, Stanislaus, Merced, Madera, and San Joaquin). (In millions)*

| Combination | Activity | Direct Impacts | Indirect Impacts | Induced Impacts | Total Impacts | Total SAM Multiplier |
|---|---|---|---|---|---|---|
| $80 per ton and conversion rate of 15% | Employment | 12.00 | 0.98 | 3.60 | 16.58 | 1.38 |
| | Labor income ($) | 1.072 | 0.070 | 0.175 | 1.317 | 1.23 |
| | Total value added ($) | -0.515 | 0.093 | 0.344 | -0.077 | 0.15 |
| | Output ($) | 0.072 | 0.197 | 0.568 | 0.837 | 11.56 |
| $80 per ton and conversion rate of 25% | Employment | 12.00 | 1.03 | 3.62 | 16.65 | 1.39 |
| | Labor income ($) | 1.072 | 0.073 | 0.176 | 1.321 | 1.23 |
| | Total value added ($) | -0.493 | 0.101 | 0.346 | -0.046 | 0.09 |
| | Output ($) | 0.121 | 0.207 | 0.571 | 0.898 | 7.45 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $80 per ton and conversion rate of 35% | | | | | | |
| | Employment | 12.00 | 1.07 | 3.64 | 16.71 | 1.40 |
| | Labor income ($) | 1.071 | 0.077 | 0.177 | 1.326 | 1.24 |
| | Total value added ($) | -0.473 | 0.102 | 0.348 | -0.022 | 0.05 |
| | Output ($) | 0.169 | 0.215 | 0.574 | 0.958 | 5.67 |
| $280 per ton and conversion rate of 15% | | | | | | |
| | Employment | 12.00 | 0.98 | 3.63 | 16.61 | 1.38 |
| | Labor income ($) | 1.071 | 0.07 | 0.177 | 1.318 | 1.23 |
| | Total value added ($) | -0.334 | 0.093 | 0.347 | 0.106 | -0.32 |
| | Output ($) | 0.253 | 0.195 | 0.573 | 1.023 | 4.03 |
| $280 per ton and conversion rate of 25% | | | | | | |
| | Employment | 12.00 | 1.03 | 3.67 | 16.70 | 1.39 |
| | Labor income ($) | 1.072 | 0.073 | 0.179 | 1.324 | 1.24 |
| | Total value added ($) | -0.192 | 0.098 | 0.351 | 0.257 | -1.33 |
| | Output ($) | 0.422 | 0.205 | 0.579 | 1.206 | 2.86 |
| $280 per ton and conversion rate of 35% | | | | | | |
| | Employment | 12.00 | 1.08 | 3.72 | 16.79 | 1.4 |
| | Labor income ($) | 1.072 | 0.077 | 0.181 | 1.329 | 1.24 |
| | Total value added ($) | -0.051 | 0.103 | 0.356 | 0.408 | -8.06 |
| | Output ($) | 0.591 | 0.215 | 0.587 | 1.393 | 2.35 |
| $2,512 per ton and conversion rate of 15% | | | | | | |
| | Employment | 12.00 | 1.00 | 3.99 | 16.99 | 1.42 |
| | Labor income ($) | 1.072 | 0.071 | 0.195 | 1.337 | 1.25 |
| | Total value added ($) | 1.685 | 0.094 | 0.382 | 2.162 | 1.28 |
| | Output ($) | 2.272 | 0.198 | 0.63 | 3.101 | 1.36 |
| $2,512 per ton and conversion rate of 25% | | | | | | |
| | Employment | 12.00 | 1.06 | 4.28 | 17.34 | 1.44 |
| | Labor income ($) | 1.072 | 0.075 | 0.209 | 1.355 | 1.26 |
| | Total value added ($) | 3.173 | 0.100 | 0.409 | 3.683 | 1.16 |
| | Output ($) | 3.787 | 0.211 | 0.675 | 4.673 | 1.23 |
| $2,512 per ton and conversion rate of 35% | | | | | | |
| | Employment | 12.00 | 1.13 | 4.56 | 17.69 | 1.47 |
| | Labor income ($) | 1.072 | 0.079 | 0.223 | 1.374 | 1.28 |
| | Total value added ($) | 4.661 | 0.106 | 0.437 | 5.204 | 1.12 |
| | Output ($) | 5.302 | 0.224 | 0.720 | 6.246 | 1.18 |

As shown in Table 3-4, our analysis reveals interesting insights into more economic impacts of biochar production under varying price scenarios. In particular, when biochar is priced at $80 per ton and, conversely, at a higher rate of $280 per ton, the direct Value Added takes on a noteworthy characteristic. To clarify, Value Added represents the difference between Output, primarily stemming from biochar sales and the costs associated with Intermediate Inputs, which include goods and services procured from other industries. Value Added equals the sum of Labor Income, Taxes on Production and Imports, and Other Property Income (Clouse 2020). It effectively quantifies whether revenues surpass costs or vice versa. In the context of our study, as shown in Table 3-4, in the first scenario (biochar is $80 per ton and a conversion rate of a fraction of 15%), the total Value Added amount (direct, indirect, and induced) is -$77,279.14 which is shown in the model as a negative tax. This is the amount of the required subsidy for annual biochar production of $80 per ton and a conversion rate of a fraction of 15% to break even.

A key determinant of economic impact is the Social Accounting Matrix (SAM) multiplier, displayed in the last column of Table 3-4. This multiplier reflects the additional economic activity generated as a consequence of one unit of direct economic activity originating from the biochar production industry. It is an insightful measure applicable across various economic dimensions, including Employment, Labor Income, Output, and Value Added. Therefore, it represents the additional economic activity generated because of one unit of direct economic activity of the studied industry. The Employment SAM multiplier for the first scenario (the price of biochar is $80 per ton and a conversion rate of a fraction of 15%) is 1.38. It suggests that for each person employed in the proposed biochar production industry another 0.38 jobs in the wider economy are supported. In other words, for every 100 people that are employed in the biochar industry, there would be 38 more jobs that would result in the broader economy. Similarly, in terms of financial returns, each unit-dollar spent in the same scenario yields an impressive $0.23 in labor income throughout the wider economic landscape. These multiplier effects underscore the positive ripple effects of biochar production, even when considering the lowest price and conversion rate scenario. This highlights the potential for biochar production to not only support employment but also stimulate labor income and broader economic activity. Our findings provide valuable insights into the economic dynamics of biochar production under different pricing and conversion rate scenarios. While challenges exist, particularly under the $80 per ton and 15% conversion rate scenario, the overall positive impacts, as evidenced by SAM multipliers, underscore the potential of biochar production as an economic driver. Policymakers and industry stakeholders can leverage these insights to explore strategies for enhancing the economic sustainability of biochar production in Central Valley, California, and similar regions.

We also consider two distinct scenarios to gain a comprehensive understanding of the economic dynamics surrounding biochar production. First, assuming a biochar conversion rate of 25% and a corresponding market price of $280 per ton, the outcomes, as shown in Table 3, unveil a promising economic landscape. Under these conditions, the biochar enterprise is poised to catalyze the creation of 12 full- and part-time jobs, thereby prompting a positive employment trend within the region. These jobs would collectively contribute to a substantial direct gross output of approximately $422,000. Moreover, the ripple effects of such a biochar enterprise extend beyond its immediate sphere, generating an additional 5 new full- and part-time jobs through both indirect and induced impacts.

This illustrates how biochar production, with a higher conversion rate and market price, can act as a catalyst for employment generation, fostering economic opportunities within communities and beyond the initial workforce.

Turning our attention to biochar production with a conversion rate of 15% and a significantly elevated biochar market price of $2,512 per ton, the results displayed in Table 3-4 further indicate a remarkable economic trajectory. In this scenario, the production portfolio emerges as a strong generator of economic value. Our results indicate that it would create 12 full- and part-time jobs and contribute $2,273,000 in direct gross output. Notably, this represents an eightfold increase in gross output compared to the scenario where the biochar price is set at $280 per ton. Moreover, the biochar enterprise, operating under these conditions, initiates the creation of 5 new full- and part-time jobs, echoing the positive employment trend seen in the previous scenarios. These additional jobs would emanate from both the indirect and induced impacts of the enterprise, further solidifying biochar production as a potent driver of regional economic development. While we discuss these positive economic impacts in the context of Central Valley, California, it is reasonable to anticipate that similar benefits could be realized in other regions with a comparable socioeconomic context.

### *3.5.2. Economic Impacts of Biochar Production by Counties in Central Valley, California*

Table 3-5 presents county-level regional economic impact results in Central Valley, California. These results were obtained by filtering regions. To provide a clearer explanation, when a Region filter is applied for a specific region (for example Region A), the results will exclusively display the cumulative impact within Region A. In this study, six distinct events are being examined. By selecting the Region A filter, the analysis will specifically present the combined effects on Region A that are attributable to all six events considered in the study.

*Table 3-5 The total effects on each county when biochar price is $2512 per ton and conversion rate of a fraction of 15% (In millions)*

| Combination | Impacts | Direct Impacts | Indirect Impacts | Induced Impacts | Total Impacts | Total SAM Multiplier |
|---|---|---|---|---|---|---|
| Fresno County | Employment | 2.00 | 0.23 | 0.87 | 3.10 | 1.55 |
| | Labor income ($) | 0.166 | 0.016 | 0.043 | 0.226 | 1.40 |
| | Total value added ($) | 0.520 | 0.024 | 0.084 | 0.627 | 1.21 |
| | Output ($) | 0.623 | 0.052 | 0.141 | 0.816 | 1.31 |
| Kern County | Employment | 2.00 | 0.15 | 0.69 | 2.84 | 1.41 |
| | Labor income ($) | 0.193 | 0.012 | 0.033 | 0.238 | 1.23 |
| | Total value added ($) | 0.294 | 0.018 | 0.065 | 0.377 | 1.28 |
| | Output ($) | 0.392 | 0.037 | 0.107 | 0.537 | 1.37 |
| Madera County | Employment | 2.00 | 0.11 | 0.28 | 2.39 | 1.20 |
| | Labor income ($) | 0.102 | 0.009 | 0.014 | 0.124 | 1.22 |
| | Total value added ($) | 0.118 | 0.010 | 0.028 | 0.156 | 1.33 |
| | Output ($) | 0.213 | 0.02 | 0.047 | 0.280 | 1.32 |
| Merced County | Employment | 2.00 | 0.13 | 0.62 | 2.75 | 1.38 |
| | Labor income ($) | 0.213 | 0.009 | 0.028 | 0.250 | 1.17 |
| | Total value added ($) | 0.238 | 0.011 | 0.056 | 0.305 | 1.28 |
| | Output ($) | 0.335 | 0.024 | 0.094 | 0.453 | 1.35 |
| San Joaquin County | Employment | 2.00 | 0.16 | 0.70 | 2.86 | 1.43 |
| | Labor income ($) | 0.209 | 0.012 | 0.034 | 0.256 | 1.22 |
| | Total value added ($) | 0.165 | 0.015 | 0.068 | 0.248 | 1.50 |
| | Output ($) | 0.261 | 0.028 | 0.108 | 0.398 | 1.53 |
| Stanislaus County | Employment | 2.00 | 0.21 | 0.84 | 3.05 | 1.52 |
| | Labor income ($) | 0.188 | 0.012 | 0.042 | 0.243 | 1.29 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Total value added ($) | 0.351 | 0.017 | 0.081 | 0.449 | 1.28 |
| | Output ($) | 0.450 | 0.036 | 0.131 | 0.617 | 1.37 |
| All other Counties in California | | | | | | |
| | Employment | - | 0.06 | 0.68 | 0.74 | - |
| | Labor income ($) | - | 0.006 | 0.051 | 0.057 | - |
| | Total value added ($) | - | 0.010 | 0.090 | 0.100 | - |
| | Output ($) | - | 0.018 | 0.148 | 0.166 | - |

For the sake of brevity, we focus on results associated with a biochar price of $2,512 per ton and a biochar conversion rate of 15%. One of the most significant outcomes of this analysis pertains to employment generation, which carries substantial implications for each county in the region. The results suggest that a biochar enterprise could serve as a notable source of job creation, with the number of new full- and part-time positions varying somewhat between counties. Biochar enterprise is estimated to create a range of 2.39 to 3.10 new full- and part-time jobs per county per year. Madera County, characterized by its unique economic landscape, is expected to witness the formation of the fewest new jobs. This outcome can be partly attributed to Madera County's limited biomass availability, which may not align as closely with the biochar industry compared to other counties. However, these jobs would still directly contribute to gross output by $280,268, which is considerable. Kern County, much like Madera County, demonstrates a solid potential for job creation, with an estimated 2.84 new positions per year. This alignment with Madera County may be attributed to shared economic characteristics or regional factors. In contrast, Fresno County emerges as a standout in this analysis, boasting the highest anticipated job creation figures, at approximately 3.10 new positions annually. Beyond contributing significantly to local employment, Fresno County's robust performance extends to its Gross Domestic Product (GDP). Notably, this county is poised to harness the greatest indirect and induced economic impacts, further solidifying its status as a focal point for biochar-related economic growth in the region.

It is also noteworthy to identify the sectors that would indirectly benefit the most as a result of the newly created jobs from all counties. Based on our findings, it was evident that certain sectors would stand to gain substantially from the creation of new jobs in all Central Valley counties. Noteworthy among these are the Commercial and Industrial Machinery and Equipment, Repair and Maintenance sector, as well as the Electronic and Precision Equipment Repair and Maintenance sector, along with the Insurance Agencies, Brokerages, and Related Activities sector. These sectors demonstrate a heightened propensity to benefit indirectly from the economic activity generated by the biochar industry.

Biochar production in Central Valley contributes approximately $627,450.64 to this region's GDP. Following closely are Stanislaus County with $448,712.27, Kern County with $376,810.67, Merced County with $305,241.67, San Joaquin County with $247,695.42, and Madera County with $156,084.79. These figures illustrate the substantial financial inflow generated by the biochar sector and underline its role as a key driver of economic growth in these counties.

Shifting our focus to Social Accounting Matrix (SAM) multipliers, Fresno County once again takes the lead, this time in terms of Employment. Our findings suggest that for every new hire in the biochar industry in Central Valley, an additional 0.55 full- and part-time positions are anticipated to be created in the broader Fresno County economy. This finding accentuates the ripple effect of biochar investments within Fresno County, showcasing its capacity to stimulate employment growth beyond the industry itself. This heterogeneity in employment impacts across Central Valley counties can be attributed, in part, to variations in almond production levels in each county, underscoring the interplay between agricultural practices and regional economic dynamics.

Finally, the last row of Table 3-5 provides a comprehensive view of the biochar industry's influence on the broader California economy. While there are no direct impacts due to the absence of biochar production in other counties, the indirect and induced impacts are unequivocally positive, totaling $99,657.61 in Value Added. This outcome signifies a notable boost to the state's economic development resulting from biochar-related economic activities, further affirming the sector's potential as a catalyst for economic growth, not only within Central Valley but also across the entire state.

### 3.6. Conclusion and policy implications

This chapter proposes a solution to socio-economic and environmental issues in farm-adjacent communities and demonstrates the potential regional economic impacts of biochar production in California’s Central Valley. Based on our findings, the following conclusions and policy implications can be drawn:

- Biochar production has the potential to impact the local economy through the creation of new employment opportunities. The creation of new jobs would be not only within the biochar sector but also within its supply chain. The number of potential part- and full-time jobs that would be created ranges from 16.56 to 17.69 depending on the range of biochar prices and conversion rates considered here. These numbers are plausible and comparable with findings from other studies (He et al., 2016; Joshi et al., 2012; Nematian et al., 2021) on biomass which suggests that while biochar remains a plausible environmental management strategy, its production has positive ripple economic impacts (e.g., job creation).

- Depending on the biochar price and conversion rates considered here, biochar production could contribute about $1.3 million per year to the labor income of Central Valley's local economy. This finding suggests that biochar has the absolute potential to improve the income levels of both households and industries involved in the sector which would also significantly impact positively on people's welfare.
- There is a substantial contribution of biochar to the Gross Domestic Product (GDP), a value that ranges from $2.1 million when the conversion rate is 15% and the price is $2,512 per ton to $5.2 million when the price and conversion rates are $2,512 $ per ton and 35%. Similarly, the contribution to gross output would be positive as well, regardless of the conversion rates and price. These findings imply that support for increased biochar production and a market is required.
- Direct, indirect, and induced impacts are higher when there is more available biomass in a region. For example, Fresno County has the highest almond biomass which results in the highest Output and Value added. This means by increasing biochar production and using all sources of crop residue we can expect positive impacts on the overall economy.
- County-level impact results indicate that all the counties would benefit in terms of employment, labor compensation, value addition, and gross output. Notable was Madera County which would have the lowest economic returns among the

> rest. Fresno County stood out across all economic indicators suggesting that it would be the most fertile ground to initiate biochar production. While the other counties had lower values of economic indicators, they had comparable social accounting matrix (SAM) multipliers which provide evidence that economic returns from investment in biochar and its market are high. These findings, as in Palansooriya et al. (2019) indicate that biochar production is an economically beneficial endeavor whose market and production should be promoted in the U.S. and other regions with a biomass problem.

While our study primarily focuses on estimating regional economic impacts in Central Valley, California, it's important to acknowledge certain caveats, as is common in empirical research. First, biochar exhibits significant potential for generating syngas rich in carbon monoxide (CO) and hydrogen ($H_2$), making it a sustainable alternative to conventional fossil fuel-based syngas (Rathore & Singh, 2022). However, it's important to note that while biochar gasification offers a reduction in greenhouse gas emissions, the combustion of syngas may still produce air pollutants that necessitate emission control systems. To maximize the environmental benefits of biochar gasification, further research should explore optimal gasifier operating conditions and containment solutions.

Second, the integration of biochar into clean cook stove designs presents an avenue for mitigating harmful emissions compared to traditional solid cooking fuels. Biochar combustion not only provides energy for cooking but also reduces emissions of particulate matter and carbon monoxide, which are known to pose risks to indoor air quality and human health (Shamim et al., 2015; Yaashikaa et al., 2020). Research into cook stove optimization, focusing on enhanced fuel efficiency and emission reduction, warrants continued attention to advance sustainability. It is crucial, however, to emphasize that the procurement of feedstock and the production of biochar stoves should be carried out in a manner that minimizes lifecycle impacts to avoid unintended tradeoffs.

Furthermore, it's important to recognize that the availability of agricultural production and biomass resources can fluctuate due to various factors, including changes in weather patterns and resource availability. In the context of our model, such fluctuations can impact both the model's output, particularly in terms of revenue from biochar sales, and its inputs, such as the cost of biochar production. Technological advancements, for instance, may lead to cost reductions in biochar production. Moreover, in this study, we focused only on one feedstock, but biochar can be produced from a variety of feedstocks, which can result in an increase in production volume and profitability.

However, for the purpose of this chapter, the data we collected was up to date and with most alternative pricing and biochar conversion rates that are reasonable when adjusting in line with the IMPLAN model's sectoral numbers. Results from this chapter are novel and judicious considering the potential costs and revenue for biochar production. It is possible that biochar pricing and costs of production may not be similar in other countries, but these findings provide sound evidence of economic benefits associated with biochar production with an established market and continuous production. Moreover, our results are credible, especially at a time when the global world continues to deal with the increasing biomass and agricultural waste problem which is projected to worsen by 2050 (FAO 2017).

In sum, the practical applications of this research are:

1. Biochar market expansion: By analyzing the economic dynamics of biochar production within a particular region, stakeholders can identify opportunities and challenges. This insight allows them to develop strategies to expand the biochar market more effectively. For example, they can pinpoint areas where biochar has the most potential to be integrated into existing agricultural practices.
2. Biochar price determination: An understanding of regional economics helps in setting competitive and fair prices for biochar products. Pricing is a critical factor in attracting both producers and consumers.
3. Resource allocation: Knowing the economics of biochar production allows for efficient resource allocation. For instance, it helps in deciding where to establish production facilities, ensuring proximity to feedstock sources and potential markets. This strategic placement minimizes transportation costs and reduces the environmental footprint of biochar production.
4. Policy development: Governments and regulatory bodies can use economic insights to develop policies that support the growth of the biochar industry.
5. Investment attraction: Understanding regional economics makes the biochar sector more attractive to investors.

Although we made some assumptions along the way, the list of scenarios considered here is comprehensive enough to be able to reduce the level of uncertainties and give a better understanding of the potential outcomes. The connection between biochar price, amount of biomass, conversion rates, and the immediate need for finding a sustainable biomass management strategy discussed here can pave the way for biochar market development.

### 3.7. Acknowledgments

Chapter 3, in full, has been published as it may appear in Nematian, Maryam, John N. Ng’ombe, and Catherine Keske. "Sustaining agricultural economies: regional economic impacts of biochar production from waste orchard biomass in California's Central Valley." Environment, Development and Sustainability (2023): 1-21. https://doi.org/10.1007/s10668-023-03984-6. The dissertation author was the primary researcher and author of this paper.

# Chapter 4 Social Discount Rate Selection for Investments in Biochar Projects for Climate Change Adaptation in the United States

## 4.1. Abstract

There is a growing concern regarding the evaluation of public projects, particularly those that have long-term social and environmental impacts on the nation. The conventional method for assessing the social value of an investment project involves calculating the present value of its estimated net benefits over time. Using a single discount rate for all projects, could underestimate or overestimate the profitability of a project. Moreover, this approach fails to acknowledge the importance of climate change mitigation projects. Therefore, choosing an accurate project-specific discount rate is of high importance when assessing public projects. This study aims to characterize environmental–economic discounting models calibrated for biochar investments in the United States, with a particular focus on its potential for mitigating climate change and associated risks. This is done through two separate approaches. Approach one is based on a modified Ramsey formula proposed by Gollier, (2010) to account for uncertainties in the growth of economy and the link between environmental quality and economic growth. The second approach is Consumption Capital Asset Pricing Model (CCAPM) based model proposed by Weitzman (2013). The first model yields a discount rate of 1.7%, while the second model suggests a declining rate of 5.96%. We recommend incorporating both rates in the biochar cost-benefit analysis and conducting a sensitivity analysis for a more comprehensive assessment.

## 4.2. Introduction

There is no denying that the increasing emission of greenhouse gases, resulting from our collective actions, will have long-lasting consequences on the environment for centuries to come. Therefore, it is imperative that we take immediate action to address this pressing challenge. However, the dilemma lies in determining the most efficient way to allocate our current resources for the benefit of future generations while ensuring overall well-being and welfare.

Cost-benefit analysis (CBA) is a well-established approach that can effectively address this challenge and evaluate long-term projects. It is frequently employed in the assessment and decision-making processes to assist policymakers and investors in making optimal choices amidst numerous competing priorities and limited financial resources (Brzozowska, 2007). By employing CBA, decision-makers can quantitatively assess the economic, social, and environmental impacts of proposed projects. CBA involves identifying and valuing the costs involved, such as direct, indirect, and intangible costs. Simultaneously, it considers the benefits, which may encompass improvements in public health, enhanced quality of life, increased productivity, environmental preservation, and other tangible or intangible gains. The objective of this intricate analysis is to prioritize investment opportunities in a manner that maximizes intertemporal welfare, emphasizing the well-being and prosperity of both present and future generations.

In the early stages of conducting a CBA, two primary issues emerge. First, the inquiry revolves around determining the non-monetary benefits and costs that should be included in the analysis. Second, a critical consideration is the determination of the accurate discount rate, commonly referred to as the social discount rate (SDR) in the context of public projects. The discount rate plays a vital role in calculating the present value of costs and benefits that are anticipated to materialize in the future (Muñoz Torrecillas et al., 2019).

In this chapter, our focus centers on a fundamental component of the CBA toolkit: the discount rate. We discuss the appropriate model and estimate this rate specifically for biochar projects. Biochar is a charcoal-like substance that is produced through the process of pyrolysis, which is the decomposition of organic matter in the absence of oxygen. This process results in a product rich in carbon that can be used as a soil amendment in agriculture, horticulture, and environmental remediation. Biochar has the potential to sequester carbon, which makes it an attractive option for mitigating climate change (Gonzales et al., 2021; Lehmann et al., 2011; Roberts et al., 2010). Moreover, biochar is a sustainable alternative to traditional agricultural management practices, like open field burning, which can emit high levels of greenhouse gases like methane and nitrous oxide that can lead to negative externalities such as climate change through different processes.

Despite all the potential benefits, the biochar market is still in its infancy (Major, 2011; Zafar et al., 2023). One of the factors limiting the growth of the biochar market is the limited access to capital and technology (Nematian et al., 2021). Biochar production requires significant investment in equipment and infrastructure, and many small-scale farmers and producers do not have the resources to invest in these technologies.

Inconsistent policy frameworks have also hindered the growth of the biochar market. In the U.S., there is no clear policy or regulatory framework for the production and use of biochar, which creates uncertainty for investors and producers. This lack of policy guidance can make it difficult for biochar producers to obtain the necessary permits and licenses and can also make it difficult for them to access subsidies and other incentives that would help to make their operations financially viable (Pourhashem et al., 2019).

To develop effective policies for biochar, it is important to conduct a CBA to account for all costs and benefits occurring in the life of the project. Since the benefits and costs associated with biochar production and application extend over a significant time, it is necessary to use an appropriate discount rate to convert them into their present value (Poudineh, 2020). Although there has been a significant amount of research conducted on the economic feasibility of biochar, there is no consistent use of discount rates.

A social discount rate (SDR) can make a significant change in policy conclusions. However, finding an appropriate rate is challenging as there is not a single rate that can be used for different analyses. Studies have used a wide range of rates varying from 1 to 15 percent (M. Harrison, 2010). The Stern Review suggested an SDR of 1.4% which created a case for an immediate increase in the carbon price (Stern, 2007), while other studies suggested higher rates, for example, Nordhaus (2007) suggested a 5.5% rate. The results of a survey of 2,160 economists show every individual believes in a different SDR (-3%-27%) (Weitzman, 2001). The significant debate among scientists on a particular SDR suggests a need for more comprehensive research on this subject.

A more refined way to determine the suitable discount rate is to calculate a rate tailored to each project. According to a recent survey, three-quarters of the respondents suggest the utilization of project-specific discount rates (Gollier et al., 2023). For instance, the survey reveals that, on average, railway infrastructures should be discounted at a higher rate compared to hospitals and climate mitigation projects (Gollier et al., 2023). This result reinforces the need for project-specific discount rates.

The use of SDR in biochar CBA holds significant importance for multiple reasons. Primarily, biochar has significant environmental benefits that extend well beyond the conventional market timeframe. Notably, the sequestration of carbon in biochar possesses the potential to effectively mitigate climate change, which its consequences will be experienced for generations to come. Employing market discount rates may undervalue these benefits, thereby resulting in suboptimal decision-making processes.

Moreover, the use of SDR involves ensuring fairness in the distribution of benefits and costs among various societal groups. For instance, the costs of biochar production may accrue to the farmers who use it as a soil amendment, while the benefits may be borne by the local communities who experience the positive impacts of biochar. By using SDRs, decision-makers can ensure that the benefits and costs are fairly distributed across different groups, considering the social and ethical dimensions of the decision.

Finally, the use of SDR also considers the uncertainty and risk associated with biochar production and use. There is still much to learn about the environmental impacts of biochar, and the long-term effects of its use on soil health and crop yields are not yet fully understood. By using SDR, decision-makers can account for this uncertainty and make decisions that are robust to different possible scenarios.

Based on the above reasons, the question is: What rate should be used for biochar investments? In general, for public projects there are two common approaches for SDR calculation: Social Rate of Time Preference (SRTP) and the Social Opportunity Cost (SOC) approach. We will discuss both approaches for biochar projects in the United States.

In the sections that follow, first, we undertake a review of the existing literature on the economic analysis of biochar, exploring the discount rates used in their analysis. Section 4.4 of this chapter includes discussion of the materials and methods employed in our analysis. We outline the specific parameters utilized to formulate the proposed biochar

SDR model. Section 4.7 contains the results of the analysis. Conclusions are presented in Section 4.8.

### 4.3. Related Literature

In this section, we provide a summary of the various discount rates that have been employed in the existing body of biochar economic analysis literature. Sahoo et al. (2019) used a Discounted Cash Flow Rate of Return (DCFROR) model to evaluate the economic feasibility of producing biochar from forest residues using portable manufacturing systems in near-forest settings. They used a 16.5% discount rate (nominal, before finance and tax) and 2% inflation per year for a 10-year project (Sahoo et al., 2019). Dickinson et al. (2015) used a discount rate of 0.10 for the capital costs of the facility and a 5% discount rate for yield benefits. They varied the rates from 3 to 7% to evaluate the effect of the discount rate on the CBA results. The analysis showed discount rate contributed moderately to net present value variation in both of their scenarios (Dickinson et al., 2015). Ng et al. (2017) using a Monte Carlo simulation model, performed a cost-benefit analysis to assess the implementation of a gasification biochar production system in a hen layer farm. In their study, the discount rate was defined as a triangular distribution with lower, mode, and upper limits of 1%, 8%, and 15%, respectively (Ng et al., 2017). Latawiec et al. (2021) employ a comprehensive CBA framework to assess the economic implications of biochar utilization. The authors analyzed various factors, including input costs, crop yields, soil fertility improvements, and potential carbon sequestration benefits associated with biochar application in soybean production; they used a discount rate of 9% for their analysis. Campbell et al (2018) performed a sensitivity analysis showing that different discount rates (4%,10%,16%) can significantly change the net present value of the project

The utilization of various discount rates in the literature of biochar economic analysis can be attributed to the absence of a discount rate specifically tailored for biochar. Due to the unique nature of biochar as a product, which has both economic and environmental aspects, researchers have faced challenges in determining an appropriate discount rate that adequately captures the multidimensional benefits and costs associated with biochar implementation. We close the gap in literature by estimating SDR specific to biochar.

### 4.4. Materials and Methods

The discount rate to adjust future cash flows to their present value, plays a crucial role in Net Present Value (NPV) calculations. This rate, as denoted by the variable $r$, is shown in the Eq (4-1). $R_t$ refer to net cash flow at time t.

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} \tag{4-1}$$

The main objective of this chapter is to estimate the discount rate of the biochar market, considering the environmental and climate change mitigation potentials (externalities) of the project. An externality exists when one person or firm's consumption or production choices negatively or positively affect another entity without permission or compensation (Rosen, 2004). In biochar soil application, positive externalities (environmental benefits) are not priced which causes a market failure (Pourhashem et al., 2019). Since market interest rates cannot reflect the externalities in environmental projects, we intend to find a rate that can be used for biochar cost-benefit analysis.

Figure 4-1 shows two main approaches that are commonly used to determine SDRs. The social rate of time preference (SRTP) in discounting is grounded on the concept that the costs and benefits of a policy can be represented as modifications in consumption patterns over time; in this context, the discount rate should be the rate at which society is willing to exchange present for future consumption (Advisers, 2017). In order to calculate the SRTP we use an Ecological Discounting model suggested by Gollier, (2010) which is based on the growth theory developed by Ramsey, (1928). The Social opportunity cost of capital (SOC) alternatively emphasizes the consideration of opportunity costs, questioning if a policy's overall return is at least equal to the return to the alternative usage of the same resources by the private sector (Advisers, 2017). In the upcoming sections, we will elaborate on these methods.

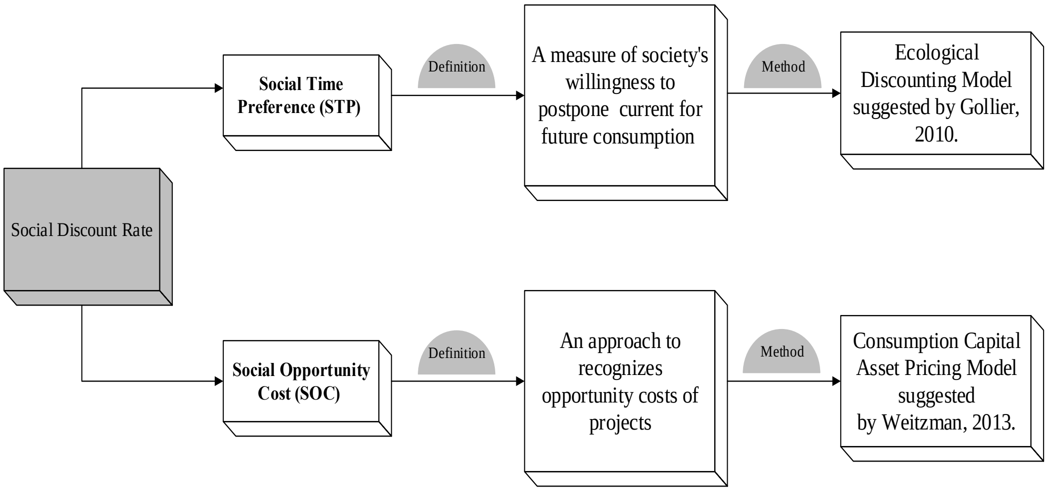

*Figure 4-1 Summary of two most common approaches to estimate social discount rates.*

## 4.5. Social rate of time preference

Calculating the SRTP aims to strike a balance between valuing the well-being of the present generation while accounting for the welfare of future generations and ensuring intergenerational fairness (Davidson, 2014; Scarborough, 2011; Weikard & Zhu, 2005; Zhuang et al., 2007). Currently, in the United States, the after-tax real (adjusted for inflation) rate of return on fixed-rate Treasury bills is frequently employed as an estimate for the SRTP (Advisers, 2017). However, considering that the overall welfare of society is influenced by consumption, SRTP should account for the weights society places on present and future consumption patterns. To estimate these weights, a social welfare function (SWF) should be defined (Moore et al., 2013).

As shown in Eq (4-2), the SWF is determined by the utility associated with income or consumption.

$$SWF = \int_{t=0}^{\infty} e^{-\delta t} U(X_t) dt \tag{4-2}$$

$X_t$ represents consumption in the future. These terms demonstrate a broad understanding of consumption, which not only includes traditional goods and services but also incorporates environmental benefits and damages. $U(X_t)$ characterizes utility obtained from consuming $X_t$ in time t. $\delta$ is the utility discount rate or rate of pure time preference. It causes a decrease in the worth of future utility compared to present utility (Karp & Traeger, 2013). Maximizing this function will give us the discount factor. The result is known as the Ramsey formula (Ramsey, 1928).

In the following sections, we discuss the Ramsey Rule, the extension of this rule to account for non-monetary benefits (ecological discounting), and the data we used to estimate the SDR specific to the biochar sector.

### 4.5.1. Ramsey Rule

Ramsey addressed the question regarding the optimal amount a nation should save and invest to maximize long-term benefits (Ramsey, 1928). This analysis plays a key role in economists' decisions on balancing present and future benefits, guiding resource allocation over time (Polasky & Dampha, 2021).

Ramsey’s formula, which establishes a connection between the social discount rate, the utility discount rate, and a growth factor, can be stated as follows (Ramsey, 1928):

$$r = \delta + \gamma g \tag{4-3}$$

As explained, the pure rate of time preference ($\delta$) refers to the rate at which individuals or societies prefer receiving immediate benefits compared to future ones. This reflects the inherent inclination for immediate gratification or benefits over delayed ones. $\gamma$ denotes the relative aversion to intertemporal inequality. It quantifies the percentage change in marginal utility when consumption increases by one percent, and $g$ is the rate of growth of consumption. The product of the consumption growth rate and the elasticity of marginal utility ($\gamma g$) illustrates the relationship between the current and the future marginal utility of consumption. Common reasoning and empirical observations indicate that as consumption increases, marginal utility tends to decrease. To motivate an investor to save and forego current consumption, a higher amount of future consumption needs to be offered (Polasky & Dampha, 2021).

Each parameter in the Ramsey rule can be estimated in two main ways: a descriptive (positive) approach or a prescriptive (normative) approach. In the descriptive approach, real-world observations are used to estimate each of the parameters, while in a prescriptive approach, the parameters are based on ethical principles (M. Harrison, 2010). Zhuang et al. (2007) showed $\delta$ (the pure rate of time preference) ranges from 0 to 3 percent. $\gamma$ (The elasticity of marginal utility of consumption) ranges from 0.2 to 4. The most common rates used in the literature are shown in Table 4-1.

*Table 4-1 Social discount rates cited in the literature*

| | $\delta$ | $\gamma$ | g | r |
|---|---|---|---|---|
| (Nordhaus, 2007) | 1.5 | 2 | 2 | 5.5 |
| (Treasury, 2003) | 1.5 | 1 | 2 | 4.5 |
| (Stern, 2007) | 0.1 | 1 | 1.3 | 1.4 |
| (Gollier, 2006) | 0 | 2-4 | 1.3 | 2.6-5.2 |
| (Weitzman, 2007) | 2 | 2 | 2 | 6 |
| (Arrow et al., 2004) | 0.5 | 2-4 | 1.5 | 3-6 |

### *4.5.2. Extending the Ramsey rule to uncertainty*

Uncertainty is inherent in daily life, making it difficult to optimize our lifetime welfare. To determine the optimal savings level, we must estimate the future utility gain of transferring wealth despite limited knowledge about future income. This uncertainty underscores the importance of decisions for the future (Gollier, 2013). Considering the potential effects of natural resource scarcity, it is probable that future economic growth rates will decrease. The ongoing degradation of our environment and depletion of natural resources could even result in a negative GDP per capita growth (Gollier, 2013).

For discounting biochar projects, we propose using ecological rate ($r_{1t}$) Eq (4-4) suggested by Gollier, (2010). The Ramsey formula Eq (4-3) is extended with the inclusion of a precautionary saving argument, which takes into account the consumers' response to uncertainty about the future. The rationale behind reducing the discount rate when we are uncertain about future environmental changes is grounded in the concept of diminishing marginal utility. When the convex nature of marginal utility and the unpredictability of the environment intersect, it becomes apparent that our benefits from the environment will decrease as we utilize more of it. Therefore, it is prudent to lower the discount rate in response to this uncertainty (Gollier, 2010).

In Table 4-2, we have explained the parameters utilized in Eq (4-4). As explained, the key assumption in Gollier's extension is that the level of consumption in the SWF is uncertain. By considering this uncertainty, it allows for a more comprehensive analysis of the costs and benefits of environmental projects over extended periods.

$$r_{1t} = \delta + (\rho\gamma_2 + \gamma - 1)(g - 0.5\ (\rho\gamma_2 + \gamma)\sigma) \tag{4-4}$$

*Table 4-2 Definition of parameters used in ecological rate (Eq. (4-4))*

| Parameters | Explanation |
|---|---|
| $\delta$ | the rate of pure time preference, or the rate of impatience |
| $\rho$ | elasticity of environmental quality to changes in GDP per capita |
| $\gamma_2$ | aversion to environmental risk |
| $\gamma$ | the elasticity of marginal utility of consumption |
| $g$ | projected long-run average annual rate of growth in per-capita real consumption |
| $\sigma$ | the standard deviation of the growth of consumption per capita |

The objective of this study is to suggest discount rates that consider the climate change mitigation potentials associated with biochar investments. The primary innovation of this framework lies in the incorporation of environmental quality, which is novel as it introduces the Environmental Justice Index (EJI) as its defining component for the first time. In the following section, we provide an explanation of the EJScreen tool, which was utilized to access environmental and demographic information for various locations across the United States.

### *4.5.3. EJScreen*

EJScreen is a screening tool developed by the United States Environmental Protection Agency (EPA) to support environmental justice analysis. It provides environmental and demographic data to help identify areas that may be disproportionately affected by environmental hazards (U.S. Environmental Protection Agency (EPA), 2019).

EJScreen combines environmental and demographic indicators to generate maps and reports that can assist in understanding potential environmental justice concerns in specific locations. The tool uses publicly available data from various sources, including the U.S. Census Bureau and EPA databases, to assess factors such as air quality, water quality, waste sites, demographic characteristics, and socioeconomic status. The primary goal of EJScreen is to identify areas where populations may face higher environmental burdens or potential exposure to pollutants.

EJScreen reports 13 environmental justice indexes, and each index combines environmental and demographic indicators to generate an overall assessment of environmental justice concerns in a specific location. It considers both the potential environmental burden and the social vulnerability of the affected population (U.S. Environmental Protection Agency (EPA), 2019). Environmental Indicators used are Fine Particulate Matter ($PM_{2.5}$), Ozone, Diesel Particulate Matter, Air Toxics Cancer Risk, Air Toxics Respiratory Hazard Index, Toxic Releases to Air, Traffic Proximity, Lead Paint, RMP Facility Proximity, Hazardous Waste Proximity, Superfund Proximity, Underground Storage Tanks, Wastewater Discharge (U.S. Environmental Protection Agency (EPA), 2023).

The Demographic Index is calculated as the mean of two demographic indicators: the percentage of low-income individuals and the percentage of people of color (U.S. Environmental Protection Agency (EPA), 2019). The EJ Indexes are calculated by multiplying environmental indicators and the Demographic Index (U.S. Environmental Protection Agency (EPA), 2023).

We opted to utilize the $PM_{2.5}$ index for our model. Airborne particulate matter (PM) includes a blend of various chemical components. It is a mixture of solid particles and aerosols, consisting of small liquid droplets, dry solid fragments, and solid cores coated with liquid (California Air Resources Board, 2023). These particles are released directly from sources like construction sites, unpaved roads, fields, smokestacks, or fires (U.S. Environmental Protection Agency, 2023b). Moreover, crop residue burning is a significant contributor to direct $PM_{2.5}$ emissions, which have adverse effects on public health especially in near-farm communities (Lan et al., 2022). Therefore, to estimate ρ, we used the $PM_{2.5}$ environmental justice (EJ) index for each county in the U.S.

We collected data from the EJScreen data repository and proceeded to analyze and calculate a singular index for each state. The indexes we used are shown in Table 4-3.

*Table 4-3 EJ indexes used for each state. The national percentile uses the U.S. population as the basis of comparison.*

| **States** | **Average $PM_{2.5}$ EJ Index** | **National $PM_{2.5}$ EJ Index Percentile** |
|---|---|---|
| Alabama | 28.89 | 93.88 |
| Arizona | 5.12 | 26.53 |
| Arkansas | 25.67 | 85.71 |
| California | 28.87 | 91.84 |
| Colorado | 7.66 | 36.73 |
| Connecticut | 8.76 | 42.86 |
| Delaware | 12.66 | 51.02 |
| District of Columbia | 21.80 | 81.63 |
| Florida | 13.62 | 53.06 |
| Georgia | 34.10 | 100.00 |
| Idaho | 6.43 | 32.65 |
| Illinois | 27.88 | 89.80 |
| Indiana | 19.62 | 77.55 |
| Iowa | 8.09 | 40.82 |
| Kansas | 9.82 | 44.90 |
| Kentucky | 15.66 | 65.31 |
| Louisiana | 25.45 | 83.67 |
| Maine | 1.37 | 12.24 |

| | | |
|---|---|---|
| Maryland | 15.02 | 59.18 |
| Massachusetts | 4.51 | 24.49 |
| Michigan | 18.53 | 75.51 |
| Minnesota | 5.33 | 28.57 |
| Mississippi | 31.58 | 95.92 |
| Missouri | 14.07 | 57.14 |
| Montana | 2.12 | 14.29 |
| Nebraska | 5.53 | 30.61 |
| Nevada | 4.02 | 22.45 |
| New Hampshire | 0.61 | 4.08 |
| New Jersey | 17.62 | 71.43 |
| New Mexico | 2.52 | 16.33 |
| New York | 16.25 | 67.35 |
| North Carolina | 15.47 | 63.27 |
| North Dakota | 1.30 | 10.20 |
| Ohio | 21.17 | 79.59 |
| Oklahoma | 26.07 | 87.76 |
| Oregon | 13.84 | 55.10 |
| Pennsylvania | 16.44 | 69.39 |
| Rhode Island | 2.81 | 18.37 |
| South Carolina | 17.96 | 73.47 |
| South Dakota | 0.67 | 6.12 |
| Tennessee | 15.33 | 61.22 |
| Texas | 34.01 | 97.96 |
| Utah | 2.86 | 20.41 |
| Vermont | 1.12 | 8.16 |
| Virginia | 10.56 | 46.94 |
| Washington | 8.02 | 38.78 |
| West Virginia | 7.51 | 34.69 |
| Wisconsin | 11.66 | 48.98 |
| Wyoming | 0.06 | 2.04 |

Figure 4-2 provides a representation of the $PM_{2.5}$ EJ index percentiles across the United States. EJ Indexes are a combination of $PM_{2.5}$, population size, percent minority, and percent low-income. As depicted in Figure 4-2, Georgia, Mississippi, Texas, Alabama, and California fall within the 90th to 95th percentiles. This indicates that these states have larger groups of locations that have a high $PM_{2.5}$ EJ index.

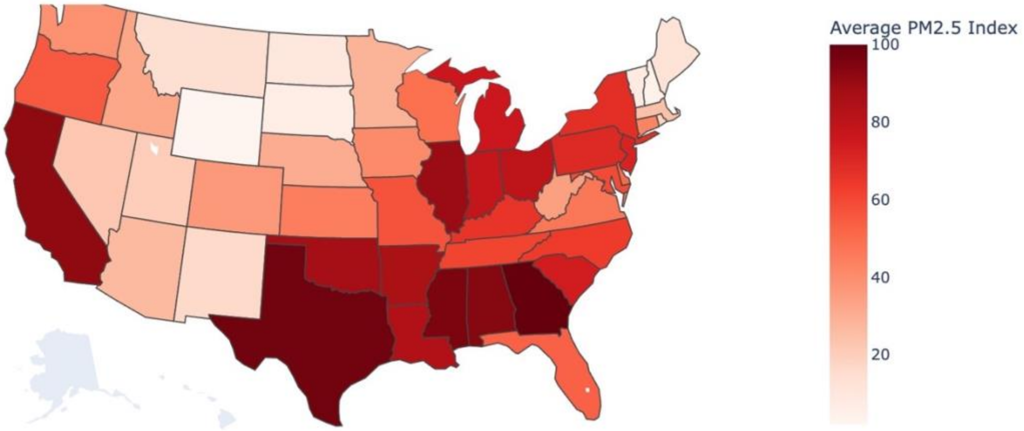

*Figure 4-2 PM$_{2.5}$ EJ index in the United States*

The elasticity of environmental quality to changes in GDP per capita is a critical factor in environmental economics, as it helps to assess the environmental consequences of economic development and make informed decisions about sustainable development and environmental policies. Utilizing EJ indexes as indicators of environmental quality is a sensible decision, as these indexes consider demographic factors. This means that they not only assess environmental conditions but also consider the socio-economic and racial demographics of the affected populations. This comprehensive approach ensures a more accurate representation of environmental disparities and their impact on marginalized communities.

### 4.6. Consumption Capital Asset Pricing Model (Weitzman-Model)

The second approach to discounting is SOC, we used a declining risk-adjusted model to estimate the SDR. A critical consideration for any investment is assessing how risk influences the expected return. The Capital Asset Pricing Model (CAPM) was developed to address this problem (Lintner, 1965a, 1965b; Mossin, 1966; Sharpe, 1964; Treynor, 1961). The Consumption Capital Asset Pricing Model (CCAPM) is an extension of the traditional CAPM. It broadens the scope of the CAPM by examining the relationship between the returns or yields of a particular asset and the overall economic activity, particularly consumption patterns. The CCAPM was developed by Breeden, (1979); Lucas Jr, (1978); and Rubinstein, (1976). It is noteworthy to mention that CAPM or CCAPM is not explicitly based on the concept of the opportunity cost of capital, but it does incorporate the idea of a risk-free rate as one of its key components. The risk-free rate in CAPM is often interpreted as a proxy for the opportunity cost of capital.

In the traditional CAPM, the primary focus is on the asset's relationship with the overall market or the market portfolio. It defines a parameter (β) to measure an asset's sensitivity to market movements. However, the CCAPM takes a more specific approach. It looks at how the returns of an asset are linked to the consumption behavior of investors and the overall economy (Duffie & Zame, 1989). A project's beta in the CAPM formula quantifies the risk of an investment. The beta for a project is unique to that project, and it may vary depending on how long the project's benefits last. In CCAPM model, beta is calculated as the elasticity of the project's net social benefit to changes in overall consumption (Gollier & Cherbonnier, 2018).

As previously mentioned, there are numerous uncertainties regarding the benefits of biochar. Therefore, as a second approach to discounting, we employ a variation of the CCAPM model modified for uncertain, long-term projects, as suggested by Weitzman, (2013). Our contribution lies in identifying a beta tailored specifically to biochar projects in the United States.

### 4.6.1. Weitzman's dynamic model

This model focuses on finding a parameter or measurement that can assess how well an investment strategy protects against extreme and catastrophic financial losses by ensuring that there are positive returns, even in the worst-case scenarios. This is an important concept in risk management and investment strategy, as it aims to minimize the impact of rare but highly damaging events on an investment portfolio (Weitzman, 2013).

Presenting the rate of return on a risk-free asset $r^f$ and the average return on all investments $r^e$, Weitzman's dynamic model is shown in Eq (4-5) (Weitzman, 2013).

$$r_{2t} = -\frac{1}{t}\ln((1-\beta_C)\exp(-r^f t) + \beta_C \exp(-r^e t)) \tag{4-5}$$

The key assumption of this model is the benefits ($B_t$) of a particular project that can be decomposed into two distinct components as shown in Eq (4-6).

$$B_t = B_t^A + B_t^C \tag{4-6}$$

In this formula, the benefit of a project at time *t* is decomposed into two terms. The first term is specific to the project itself and is independent of how the economy performs. The second term, $B_t^C$, is the average payoff on all investments in the economy. It reflects how the project's benefits are influenced by the overall economic conditions (Weitzman, 2013). This assumption suggests that the total benefits of a project can be thought of as the sum of two parts: one that depends on the project's unique characteristics and performance ($A_t$), and another that is connected to the general economic conditions and how all investments are doing in the economy ($C_t$). This breakdown enables a closer examination of where benefits come from and how they are connected to both project-specific and broader economic factors.

$\beta_C$ in Eq (4-5) is a risk measure that quantifies the fraction of expected payoffs from an investment or project that, on average, can be attributed to the uncertainties related to the macroeconomy or the overall economic conditions as shown in Eq (4-7).

$$\beta_c \equiv \frac{\mathbb{E}\, B_t^C}{\mathbb{E}\, B_t} \tag{4-7}$$

This means that:

$$1 - \beta_c \equiv \frac{\mathbb{E}\, B_t^A}{\mathbb{E}\, B_t} \tag{4-8}$$

### *4.6.2. Empirical estimation of $\beta_c$ for biochar projects in the United States*

To calculate $\beta_C$, the relationship between the systematic risk component ($C_t$) and the benefit of the project ($B_t$) can be estimated based on Eq (4-9) (Goldmann, 2019).

$$B_t = (1 - \beta_c) + \beta_c \times C_t + \varepsilon_t \tag{4-9}$$

To calculate the value of $\beta_C$, it is essential to find a time series for project benefits. In addition, GDP is used as a measure of economic risk at a macro level, the GDP frequently appears in empirical studies on this subject, as suggested by literature (Dixit & Williamson, 1989; Krüger, 2012; van Ewijk & Tang, 2003).

Considering the limited availability of comprehensive data regarding the economic and environmental benefits of biochar use, we use a stochastic process to perform a Monte Carlo (MC) simulation for biochar benefits based on the limited amount of data available. As is common in economics, we use a Geometric Brownian Motion (GBM) for MC simulation (Gollier & Cherbonnier, 2018). Eq (4-10) shows the formula for a GBM stochastic process that is commonly used in economic and especially asset pricing. To account for the saturating nature of biochar benefits, we are also adding a time varying factor to the formula. The first part of the formula will account for the volatility in the benefits over time and the time-varying component ensures that the benefits do no increase exponentially.

$$S(t) = S(0) * exp\left(\left(\mu - \frac{\sigma^2}{2}\right)t + \sigma W(t)\right) + \sqrt{\lambda t} \tag{4-10}$$

After obtaining the benefit and GDP parameters, we normalize them using the transformation method suggested by Hultkrantz et al. (2014) and Goldmann, (2019) as shown in equations (4-11) and (4-12).

$$B_t = \left[\frac{B_t - mean(B_t)}{sd(B_t)}\right] + 1 \tag{4-11}$$

$$GDP_t = \left[\frac{GDP_t - mean(GDP_t)}{sd(GDP_t)}\right] + 1 \tag{4-12}$$

Using the sampled values for biochar benefits, we calculate one $\beta_c^i, i \in [1,1000]$ per sample. Finally, we average all the calculated $\beta_c^i$ values to obtain the final $\beta_c$.

## 4.7. Results and Discussion

In this section, we first present the results of our initial model, the ecological discounting model, followed by the results of the CCAPM model.

### *4.7.1. Ecological discounting*

As elaborated in the previous section, pure time preference (δ) ranges from 0 to 3 percent. δ is essentially an indicator of how the perception of utility evolves over time. It stands apart from the monetary discount rate, which characterizes how the value of money changes over time. A positive δ signifies that utility diminishes over time, while choosing a negative δ suggests that utility appreciates as time progresses (Baum, 2007). In the context of our model, we assume that δ is zero. This choice is rooted in the understanding that, when assessing matters from a broader, extended temporal viewpoint, the fundamental purpose of the discount rate lies in the equitable allocation of utility across multiple generations, rather than being exclusively confined to an individual's lifetime (Gollier, 2006; Zhuang et al., 2007).

For parameter ρ, elasticity of environmental quality to changes in GDP per capita, as explained we used $PM_{2.5}$ EJ index. ρ refers to a measure of how responsive or sensitive environmental quality is to changes in a country's GDP per capita. In the context of SDR, this elasticity helps quantify the relationship between economic growth and environmental outcomes. Specifically, it assesses how an increase in GDP per capita (which generally signifies economic growth and higher living standards) impacts environmental quality. The elasticity can be positive, negative, or zero. A positive elasticity means that as GDP per capita increases, environmental quality also improves. This suggests that economic growth is associated with better environmental outcomes. Conversely, a negative elasticity implies that as GDP per capita increases, environmental quality deteriorates. That means economic growth might lead to more pollution or resource depletion, outweighing any positive efforts toward environmental protection. A zero elasticity means that changes in GDP per capita have no significant impact on environmental quality. This suggests that economic growth and environmental quality are not strongly linked.

On the X-axis, we depict the 2022 GDP per capita information obtained from the Bureau of Economic Analysis (Bureau of Economic Analysis, 2023), and define Y as the national $PM_{2.5}$ EJ Index percentile derived from the EPA EJScreen tool (U.S. Environmental Protection Agency, 2023a). In Figure 4-3, we have illustrated this dataset along with the corresponding regression line, which is: $y = -0.13x + 55.1$. This provides us with a ρ of -0.13, indicating that as GDP increases, environmental quality tends to decrease.

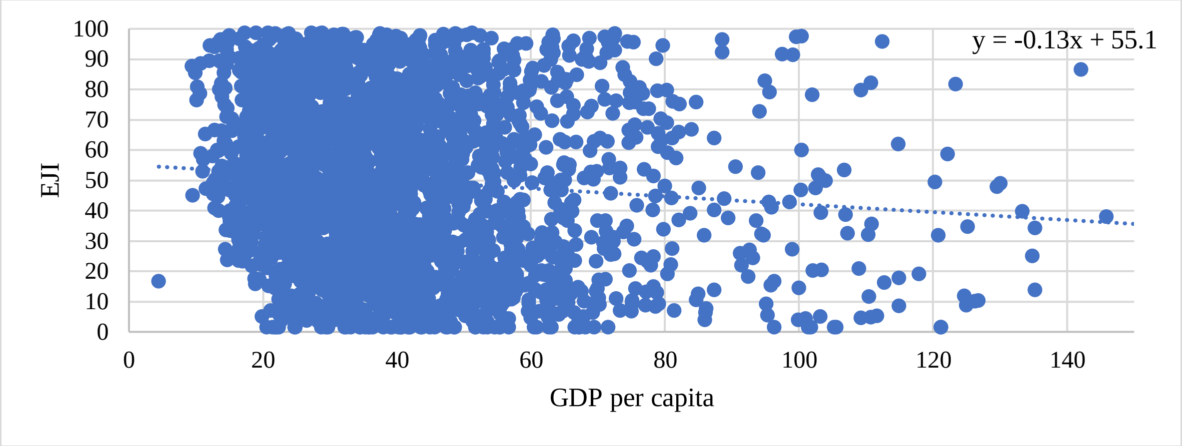

*Figure 4-3 Regression analysis between EJ index GDP per capita*

The marginal utility of consumption (γ) represents the percentage change in marginal utility resulting from a unit change in consumption (Gollier, 2013). A lower value of γ implies that marginal utility doesn't decline as significantly with increasing income. This, when coupled with the prospect of future income growth, tends to amplify the importance attributed to the well-being of future generations (Polasky & Dampha, 2021).

To calculate γ, it can be assumed that individuals' utility follows an iso-elastic utility function (Evans & Sezer, 2004). This assumption helps to model how people's happiness or well-being responds to changes in income or tax rates. They further assume that tax rates are set in a way so that each taxpayer, regardless of their income level, gives up an equal absolute amount of utility. Based on this model, the tax-based value of γ is determined by Eq (4-13). t is equal to effective marginal tax rate and T/Y is average tax rate. We use γ = 2 based on US data on federal tax rates (Evans, 2005).

$$\gamma = \frac{Log(1-t)}{Log(1-\frac{T}{Y})} \qquad (4\text{-}13)$$

Lastly, an additional environmental factor is denoted as $\gamma_2$ which represents the degree of caution or apprehension individuals exhibit regarding uncertain or adverse environmental consequences linked to a specific project, policy, or choice.

$$\gamma^* = \frac{\gamma_2 - 1}{\gamma + \gamma_2 - 2} \quad (4\text{-}14)$$

$\gamma_2$ is related to $\gamma$ and $\gamma^*$ as shown in Eq (4-14). Based on literature we assume $\gamma^* = 30\%$ (Gollier, 2010; Hoel & Sterner, 2007; Sterner & Persson, 2008), which implies $\gamma_2 = 1.4$.

The expected growth rate of per capita consumption, g, can be determined by extrapolating historical growth rates (Moore et al., 2013) . We calculated the mean annual growth rate using per capita consumption data from 1947 to 2022 (U.S. Bureau of Economic Analysis, 2023). We consider g = 2.1%

To consider the uncertainty in growth we need to calculate $\sigma$ which is a measure of the variability or risk associated with the annual growth rate of consumption. It is represented as the standard deviation or mean square deviation of the variable, and it quantifies how much the actual growth rate of consumption tends to deviate from its expected or average value. We obtained $\sigma^{1/2} = 1.95\%$. Plugging $\rho = -0.13$ in Eq (4-4) yields $r_{1t} = 1.7\%$. This ecological rate, which accounts for the biochar environment's value, is significantly lower than the discount rate used in biochar CBA literature. This difference occurs because the ecological rate considers the potentially growing willingness to pay for environmental preservation over time. Using lower rate for biochar CBA acknowledges that the environment is not a static entity, and its value can appreciate over time as society becomes more environmentally conscious.

The low social discount rate of 1.7% for biochar projects in the United States is indeed close to the risk-free rate in the U.S., typically represented by the yield on long-term U.S. Treasury bonds. As mentioned before this rate is focused on biochar’s non-market benefits, such as improved air and water quality and enhanced biodiversity. Non-market benefits tend to be undervalued when using high discount rates, so a low discount rate can better capture the full range of positive impacts. However, incorporating a risk-adjusted model to assess biochar projects is essential for a more comprehensive analysis, ensuring that all relevant risk factors are considered, and that the financial evaluation aligns with the real-world challenges and uncertainties associated with the projects. In the next section we report results of time declining risk adjusted discount rate for biochar.

### *4.7.2. Consumption capital asset pricing model*

The CCAPM-based model has three parameters as mentioned before. $r_f$ that shows risk free rate of return of an asset. $r_e$ that shows the risk equity of the economy. And finally, $\beta_C$ that shows the proportion of the payoffs at time *t* that is correlated with aggregate consumption. In this section, we will discuss the calculation of each of these three parameters separately for the United States.

#### *4.7.2.1.Risk free rate of return*

To calculate risk free rate of return, we use the data from market yield on U.S. Treasury Securities at 10-year constant maturity. Figure 4-4 shows the variation of return from 2010 to 2020. We do not include post 2020 in our analysis because of the impact of pandemic. Based on this graph, the risk-free rate of return, rounded to the closes double decimal digits is 2.21% (Board of Governors of the Federal Reserve System (US), 2023).

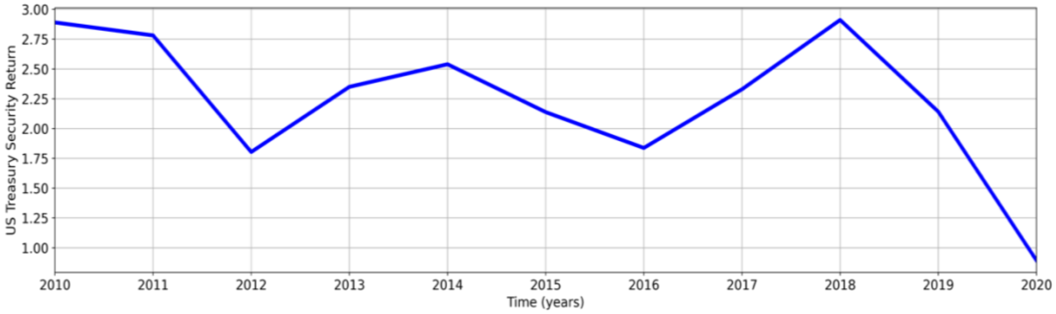

*Figure 4-4 Variation of return from 2010 to 2020*

### *4.7.2.2.Market rate of return*

The equity rate of interest can be calculated by average stock returns. For this calculation, we are using the return of Standard & Poor 500 (S&P500) as shown in Figure 4-5 (Damodaran, 2023). The average market rate of return based on this graph is 12.3%.

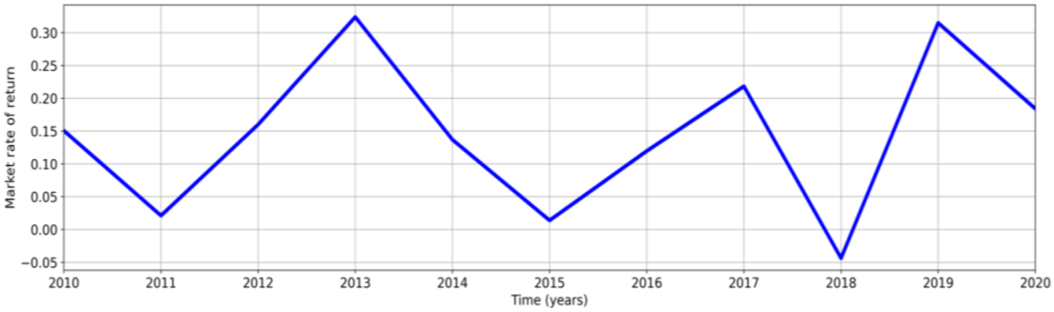

*Figure 4-5 Return of S&P500 from 2010 to 2020*

Based on this data, we determine the parameters to be applied in the calculation of the biochar discount rate, as indicated in Table 4-4.

*Table 4-4 Value of parameters used in SDR model*

| Risk free rate of return (%) | Market rate of return (%) | $\beta_C$ |
|---|---|---|
| 2.21 | 12.3 | 0.37 |

In Figure 4-6, the analysis of the SDR for a 100-year period is presented. The initial rate is determined to be 5.96% that declines to 2.7%. The average 20-year SDR is 5.16%. The variation of discount rate over time helps to better quantify the long-term benefits of biochar projects.

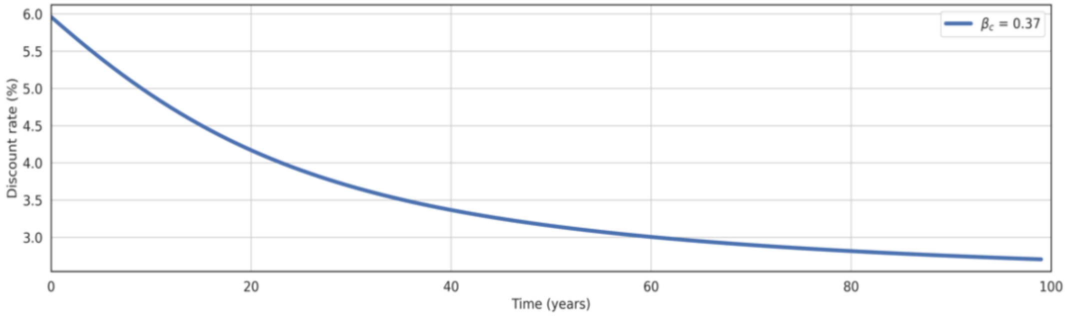

*Figure 4-6 Time-declining risk adjusted discount rates for biochar projects in the United States*

We also conduct a sensitivity analysis to assess the significance of $\beta_C$ and how alterations in this parameter impact biochar-specific discount rate. As shown in Figure 4-7, choosing different values of $\beta_C$ will drastically impact the output of this model which reinforces the need a more accurate assessment of the benefits of biochar projects.

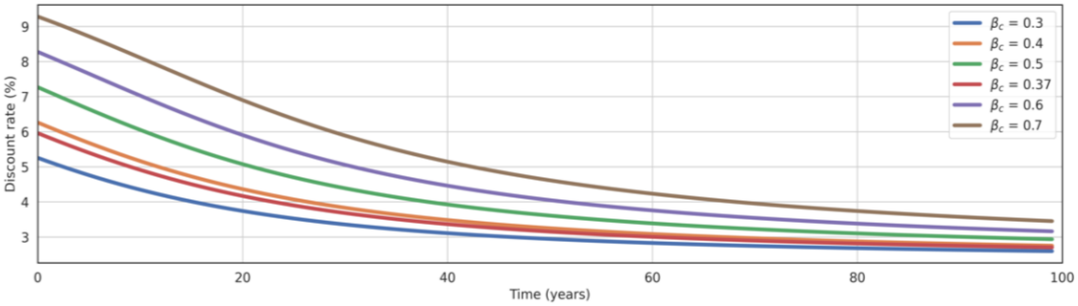

*Figure 4-7 Sensitivity analysis*

### 4.8. Conclusion and policy implications

The choice of the social discount rate plays a critical role in assessing the viability of policy interventions and comparing different projects with similar initial investment profiles and operational costs. When evaluating projects, lower discount rates give preference to those with substantial net benefits in the long term, while higher discount rates prioritize projects with immediate net benefits. Consequently, the selection of the SDR significantly influences whether a potential policy intervention exhibits a positive NPV and affects the comparative advantages of different interventions (Moore & Vining, 2018). Therefore, the careful consideration and determination of the SDR hold significant implications for the overall assessment and decision-making process surrounding policy intervention.

In this chapter, we calculated biochar specific discount rates based on two approaches. The first approach, augmented Ramsey rule, takes into account the variability of consumption. However, it does not tell how the contribution to this volatility (the covariance risk) from a specific investment under evaluation should be considered. We therefore next turn to the CCAPM model. The first model yields a discount rate of 1.7%, while the second model suggests an average 20-year SDR of 5.16%. We recommend incorporating both rates in the biochar cost-benefit analysis and conducting a sensitivity analysis for a more comprehensive assessment.

It is important to acknowledge that the accuracy of our estimate is contingent on various assumptions and data inputs. To ensure the robustness of these findings, ongoing research and continued data collection will be crucial in refining our understanding of the social discount rate for biochar projects. In light of these considerations, the estimated social discount rate of 1.7% and 5.16% should be regarded as a valuable starting point for future discussions and analyses, informing policymakers, investors, and stakeholders on the economic and social implications of biochar projects in the United States.

# Chapter 5 Conclusion

Biochar represents a promising avenue for sustainable agriculture and economic development in Central Valley California. Its potential to mitigate climate change, enhance soil health, and stimulate regional economies is substantial. The research conducted in this thesis, stochastic cost analysis, regional economic assessment, and social discount rate estimation, contributes to the understanding of the multifaceted role of biochar in this agriculturally dependent region.

As we struggle with the dual challenges of food security and environmental sustainability, biochar emerges as a viable solution with wide-reaching implications. The insights presented here can inform future decision-making and research aimed at harnessing the full potential of biochar in the context of agriculture, economics, and environmental stewardship.

This thesis has explored the economics of biochar and its potential contributions to sustainable agricultural waste management and climate change mitigation. The exploration began with a stochastic cost analysis of biochar production in Chapter 2, followed by an estimation of its regional economic impacts in Chapter 3, and an analysis of the social discount rates associated with biochar adoption in Chapter 4. In this concluding chapter, I recap the key findings, discuss their implications, and offer insights into the significance of the research.

## 5.1. Recap of Key Findings

### *5.1.1. Biochar Production Costs*

In Chapter 2, I evaluated the cost of biochar production in Central Valley California, taking into account uncertainties in the biochar production phase. Key findings include:

- The cost of biochar varies between \$448.78–\$1,846.96 $\mathrm{Mg}^{-1}$ biochar.
- Production volume, labor, and fuel costs have a substantial impact on the overall production cost.
- Smaller-scale and decentralized production methods exhibit greater cost efficiency by reducing transportation and labor costs.
- Biochar can facilitate a circular bioeconomy for agricultural waste.

### *5.1.2. Regional Economic Impacts*

Chapter 3 focused on estimating the regional economic impacts of biochar production using the IMPLAN model. Key findings include:

- The introduction of biochar production in Central Valley California is projected to create jobs, generate income, and stimulate economic growth.
- The magnitude of these economic impacts varies based on the scale of biochar production and the extent of market penetration.
- Biochar could create 16.56 to 17.69 new full- and part-time jobs/year.
- Biochar production could add about \$1.3 million per year to the labor income of Central Valley.

### *5.1.3. Social Discount Rates*

Chapter 4 explored the estimation of social discount rates for biochar, considering the long-term benefits associated with its use. Key findings include:

- Determining social discount rates for biochar involves complex considerations of intergenerational equity and the valuation of future benefits, particularly carbon sequestration and soil improvement.

- We used two models to calculate the biochar SDR. The first model yields a discount rate of 1.7%, while the second model suggests 5.16%. I recommend incorporating both rates in the biochar cost-benefit analysis and conducting a sensitivity analysis for a more comprehensive assessment.
- The choice of social discount rate can significantly affect the evaluation of biochar's long-term benefits, making it a critical parameter for policy decision-making.

## 5.2. Implications and Significance

### *5.2.1. Sustainable Agriculture*

The findings of this research demonstrate the potential of biochar to contribute to sustainable agriculture in Central Valley California. Its ability to enhance soil fertility, sequester carbon, and reduce nutrient leaching offers a promising solution to address soil degradation and water scarcity issues.

### *5.2.2. Economic Viability*

The economic analysis presented in this thesis indicates that biochar production can not only benefit the environment and agriculture but also contribute to the economic viability of the region. The creation of jobs and income in near-farm communities can alleviate some of the economic challenges faced by agricultural regions.

### *5.2.3. Policy Implications*

This research has policy implications, particularly in terms of incentivizing biochar production and adoption. Policymakers can consider strategies to support biochar development, including subsidies for small-scale producers, incentives for carbon sequestration, and the establishment of clear social discount rates.

### 5.3. Limitations

While this research has provided valuable insights, it is important to acknowledge its limitations. The cost analysis in Chapter 2 is subject to variations in market prices, which can fluctuate over time and affect the cost estimates. Moreover, we did not consider the benefits of biochar, and the breakeven analysis is based on the assumption of selling prices. The accuracy of the breakeven point is inherently tied to the reliability of these assumed prices. Fluctuations in market conditions, demand-supply dynamics, or external factors could significantly impact the actual selling prices, potentially rendering the breakeven point less accurate.

The regional economic impact assessment in Chapter 3 relies on assumptions about market demand and consumer behavior, which can change in response to economic and social factors. Moreover, when adding biochar as a new industry we started with code 15 (Forestry, forest products, and timber tract production) which includes assuming the biochar industry will be similar to this sector, and we assumed Local Purchasing Percentages (the proportion or percentage of purchases made locally within a specific area or region) for Commodity Events for Non-Marginable is by default set to 100%. This could imply that there's a strong preference or assumption that non-marginable commodities are sourced locally. For Marginable Commodity Events, the default is set to Social Accounting Matrix (SAM) value.

The estimation of social discount rates in Chapter 4 is influenced by subjective decisions and assumptions, including the choice of parameters and the valuation of benefits.

### 5.4. Future Research Directions

While this thesis provides valuable insights into the economic, and social aspects of biochar in Central Valley California, there are several avenues for future research:

- Long-term field studies to assess the actual impact of biochar on crop yields, soil quality, and carbon sequestration.
- The development of comprehensive policy frameworks that encourage sustainable biochar production and utilization.
- A study of farmer adaptation to biochar uses in agriculture.
- A more systematic way of implementing biochar and recording of its benefits to calculate a more accurate discount rate.

## References

Adhikari, S., Nam, H., & Chakraborty, J. P. (2018). *Chapter 8 - Conversion of Solid Wastes to Fuels and Chemicals Through Pyrolysis* (T. Bhaskar, A. Pandey, S. V. Mohan, D.-J. Lee, & S. K. B. T.-W. B. Khanal, Eds.; pp. 239–263). Elsevier. https://doi.org/10.1016/B978-0-444-63992-9.00008-2

Advisers, C. of E. (2017). Discounting For Public Policy: Theory and Recent Evidence on the Merits Of Updating the Discount Rate. *Council of Economic Advisers Issue Brief*.

Ahmed, A., Kurian, J., & Raghavan, V. (2016). Biochar influences on agricultural soils, crop production, and the environment: a review. *Environmental Reviews*, *24*(4), 495–502. https://doi.org/10.1139/er-2016-0008

California Senate Bill No. 705, (2003). Air quality: agricultural burning: San Joaquin Valley Unified Air Pollution Control District. An act to add Sections 41855.5 and 41855.6 to the Health and Safety Code, relating to air quality. http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200320040SB705 (accessed 10 January 2021).

Ajayi, A. E., & Horn, R. (2016). Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. *Soil and Tillage Research*, *164*, 34–44. https://doi.org/10.1016/j.still.2016.01.011

Akdeniz, N. (2019). A systematic review of biochar use in animal waste composting. *Waste Management*, *88*, 291–300. https://doi.org/10.1016/j.wasman.2019.03.054

Aksoy, B., Cullinan, H., Webster, D., Gue, K., Sukumaran, S., Eden, M., & Sammons Jr, N. (2011). Woody biomass and mill waste utilization opportunities in Alabama:

Transportation cost minimization, optimum facility location, economic feasibility, and impact. *Environmental Progress & Sustainable Energy*, *30*(4), 720–732. https://doi.org/10.1002/ep.10501

Alexander Equipment. (2020). *Morbark 2230 : 400 HP : Wood Chipper*. https://www.alexequip.com/product/morbark-2230/ (accessed March 2020).

All Safety Products. (2020a). *PolyJohn HT01-0250 250 Gallon Tank for Bulk Waste Storage | All Safety Products*. https://www.allsafetyproducts.com/ht01-0250-bulk-waste-storage-tank.html (accessed March 2020).

All Safety Products. (2020b). *PolyJohn FS3-1005 Fleet Portable Restroom Pewter Gray | All Safety Products*. https://www.allsafetyproducts.com/polyjohn-fleet-portable-restroom-fs3-1005-pewter-gray.html (accessed March 2020).

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Mäler, K.-G., Schneider, S., & Starrett, D. (2004). Are we consuming too much? *Journal of Economic Perspectives*, *18*(3), 147–172. https://doi.org/10.1257/0895330042162377

August, L., Bangia, K., Plummer, L., Prasad, S., Ranjbar, K., Slocombe, A., & Wieland, W. (2021). *California Communities Environmental Health Screening Tool, Version 4.0 (CalEnviroScreen 4.0): Guidance and Screening Tool.*

Banu, J. R., Kavitha, S., Kannah, R. Y., Kumar, M. D., Atabani, A. E., & Kumar, G. (2020). Biorefinery of spent coffee grounds waste: Viable pathway towards circular bioeconomy. *Bioresource Technology*, *302*, 122821. https://doi.org/10.1016/j.biortech.2020.122821

Baum, S. (2007). Beyond the Ramsey model for climate change assessments. *Ethics in Science and Environmental Politics*, *2007*, 15–21. https://doi.org/10.3354/esep007015

Becker, R. (2021). *Burns in San Joaquin Valley vineyards, orchards may finally end. What delayed it?* https://www.fresnobee.com/news/business/agriculture/article249434085.html (accessed 20 July 2021).

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, *159*(12), 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023

Bertoldi, G. L. (1989). *Ground-water resources of the Central Valley of California*. Department of the Interior, US Geological Survey.

Bezerra, J., Turnhout, E., Vasquez, I. M., Rittl, T. F., Arts, B., & Kuyper, T. W. (2019). The promises of the Amazonian soil: shifts in discourses of Terra Preta and biochar. *Journal of Environmental Policy & Planning*, *21*(5), 623–635.

Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, *16*(5), 832.

Board of Governors of the Federal Reserve System (US). (2023). *Market Yield on U.S. Treasury Securities at 10-Year Constant Maturity, Quoted on an Investment Basis [DGS10]*. Louis; https://fred.stlouisfed.org/series/DGS10 (accessed Nov 2023).

BONANDER TRAILERS. (2020). *2019 PJ Trailers 25' Low-Pro Flatdeck with Duals (LD) Flatbed Trailer | Bonander Trailer Sales | New*. https://www.bonandertrailer.com/2019-pj-trailers-25-low-pro-flatdeck-with-duals-ld-flatbed-trailer-dAch.html (accessed March 2020).

Breeden, D. T. (1979). An intertemporal asset pricing model with stochastic consumption and investment opportunities. *Journal of Financial Economics*, *7*(3), 265–296.

Breunig, H. M., Huntington, T., Jin, L., Robinson, A., & Scown, C. D. (2018). Temporal and geographic drivers of biomass residues in California. *Resources, Conservation and Recycling*, *139*, 287–297. https://doi.org/10.1016/j.resconrec.2018.08.022

Brinker, R. W., Kinard, J., Rummer, R., & Lanford, B. (2002). Machine rates for selected forest harvesting machines. *Machine Rates for Selected Forest Harvesting Maines, 32 p.*, 32.

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.

Brzozowska, K. (2007). Cost-benefit analysis in public project appraisal. *Engineering Economics*, *3 (53)*, 78–83.

BuildingsGuide. (2019). *Steel Building Prices, Online Estimates & Cost Quotes*. https://www.buildingsguide.com/estimates/building-cost-estimate/ (accessed March 2020).

Bureau of Economic Analysis. (2023). *GDP by State*. https://www.bea.gov/data/gdp/gdp-state (accessed Nov 2023).

California Air Resources Board. (2023). *Inhalable Particulate Matter and Health (PM2.5 and PM10)*. https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health (accessed Nov 2023).

Campbell, R. M., Anderson, N. M., Daugaard, D. E., & Naughton, H. T. (2018). Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. *Applied Energy*, *230*(June), 330–343. https://doi.org/10.1016/j.apenergy.2018.08.085

Carus, M., & Dammer, L. (2018). The circular bioeconomy—concepts, opportunities, and limitations. *Industrial Biotechnology*, *14*(2), 83–91. https://doi.org/10.1089/ind.2018.29121.mca

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. *Soil Research*, *45*(8), 629–634.

Chen, P., Yanling, C., Shaobo, D., Xiangyang, L., Guangwei, H., & Ruan, R. (2010). Utilization of almond residues. *International Journal of Agricultural and Biological Engineering*, *3*(4), 1–18.

Chen, W., Meng, J., Han, X., Lan, Y., & Zhang, W. (2019). Past, present, and future of biochar. *Biochar*, *1*, 75–87.

Cherubin, M. R., Oliveira, D. M. da S., Feigl, B. J., Pimentel, L. G., Lisboa, I. P., Gmach, M. R., Varanda, L. L., Morais, M. C., Satiro, L. S., & Popin, G. V. (2018). Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. *Scientia Agricola*, *75*(3), 255–272. https://doi.org/10.1590/1678-992x-2016-0459

Chowchilla. (2020). *Chowchilla, CA | Official Website*. http://www.cityofchowchilla.org (accessed March 2020).

Clouse, C. (2022). *Introducing Industry Impact Analysis (Detailed)*. https://support.implan.com/hc/en-us/articles/4407845065243- Introducing-Industry-Impact-Analysis-Detailed- (accessed 17 July 2022).

Connor, A. M., & MacDonell, S. G. (2005). *Stochastic cost estimation and risk analysis in managing software projects*.

Corporation Service Company. (2020). *California LLC Costs: Tax and Filing Fees | incorporate*. https://www.incorporate.com/learning-center/california/california-llc-taxes-fees/ (accessed March 2020).

Damodaran, A. (2023). *Historical Returns on Stocks, Bonds and Bills: 1928-2022*. https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/histretSP.html (accessed Nov 2020).

Davidson, M. D. (2014). Zero discounting can compensate future generations for climate damage. *Ecological Economics*, *105*, 40–47.

Deere and Company. (2020). *5125R Utility Tractor*. https://configure.deere.com/cbyo/#/en_us/configure/100813403 (accessed March 2020).

Dickinson, D., Balduccio, L., Buysse, J., Ronsse, F., van Huylenbroeck, G., & Prins, W. (2015). Cost-benefit analysis of using biochar to improve cereals agriculture. *GCB Bioenergy*, *7*(4), 850–864. https://doi.org/10.1111/gcbb.12180

Dillon, C. R. (1993). Advanced breakeven analysis of agricultural enterprise budgets. *Agricultural Economics*, *9*(2), 127–143. https://doi.org/10.1016/0169-5150(93)90008-Z

Dixit, A. K., & Williamson, A. (1989). *Risk-adjusted rates of return for project appraisal* (Vol. 290). Citeseer.

Duffie, D., & Zame, W. (1989). The consumption-based capital asset pricing model. *Econometrica: Journal of the Econometric Society*, 1279–1297.

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

English, B. C., Jensen, K., Menard, J., Walsh, M. E., Brandt, C., Van Dyke, J., & Hadley, S. (2007). Economic impacts of carbon taxes and biomass feedstock usage in Southeastern United States coal utilities. *Journal of Agricultural and Applied Economics*, *39*(1), 103–119.

Ennis, C. J., Evans, A. G., Islam, M., Ralebitso-Senior, T. K., & Senior, E. (2012). Biochar: carbon sequestration, land remediation, and impacts on soil microbiology. *Critical Reviews in Environmental Science and Technology*, *42*(22), 2311–2364.

EPA. (2022). Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020. *EPA 430-P-22-001*. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020 (accessed Nov 2022).

European Commission. (2012). *Innovating for sustainable growth: A bioeconomy for Europe*. Publications Office of the European Union. http://dx.doi.org/10.2777/6462.

European Commission. (2015). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614 (accessed 10 January 2021)

Evans*, D. J., & Sezer, H. (2004). Social discount rates for six major countries. *Applied Economics Letters*, *11*(9), 557–560. http://dx.doi.org/10.1080/1350485042000280007

FAO. (2017). *Strategic Work of FAO for Sustainable Food and Agriculture*. Food and Agriculture Organization Rome, Italy. http://www.fao.org/3/a-i6488e.pdf (accessed 10 January 2021).

Faunt, C. C., Hanson, R. T., Belitz, K., & Rogers, L. (2009). California's Central Valley Groundwater Study: A Powerful New Tool to Assess Water Resources in California's Central Valley. In *Fact Sheet*. https://doi.org/10.3133/fs20093057

Field, J. L., Keske, C. M. H., 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.

Food and Agriculture Organization (FAO). (2020). *FAOSTAT. Burning - Crop Residues*. http://www.fao.org/faostat/en/#data/GB (accessed 20 June 2021).

Galinato, S. P., Yoder, J. K., & Granatstein, D. (2011). The economic value of biochar in crop production and carbon sequestration. *Energy Policy*, *39*(10), 6344–6350.

General Motors. (2020). *2020 SILVERADO 3500 HD*. https://www.chevrolet.com/trucks/silverado/3500hd/build-and-price/summary (accessed March 2020).

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, *88*, 37–41.

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.

Goldmann, K. (2019). Time-declining risk-adjusted social discount rates for transport infrastructure planning. *Transportation*, *46*(1), 17–34.

Gollier, C. (2006). *An evaluation of stern's report on the economics of climate change*.

Gollier, C. (2010). Ecological discounting. *Journal of Economic Theory*, *145*(2), 812–829.

Gollier, C. (2013). *Pricing the planet's future: the economics of discounting in an uncertain world*. Princeton University Press.

Gollier, C., & Cherbonnier, F. (2018). *The economic determinants of risk-adjusted social discount rates*. Toulouse School of Economics.

Gollier, C., van der Ploeg, F., & Zheng, J. (2023). The discounting premium puzzle: survey evidence from professional economists. *Journal of Environmental Economics and Management*, 102882.

Gonzales, M., Harrison, B., Thao, T., Ryals, R., Ghezzehei, T. A., & Berhe, A. A. (2021). The Effects of Biochar Feedstock and Application Rate on Methane and Carbon Dioxide Emissions from Dairy Manure Composting. *AGU*.

Granatstein, D., Kruger, C. E., Collins, H., Galinato, S., Garcia-Perez, M., & Yoder, J. (2009). Use of biochar from the pyrolysis of waste organic material as a soil amendment. Final project report. *Center for Sustaining Agriculture and Natural Resources, Washington State University, Wenatchee, WA*, *168*, 167. https://doi.org/09-07-062

Groot, H., Pepke, E., Fernholz, K., Henderson, C., & Howe, J. (2018). *Survey And Analysis Of The US Biochar Industry*.

Grunwald, D., Kaiser, M., Junker, S., Marhan, S., Piepho, H.-P., Poll, C., Bamminger, C., & Ludwig, B. (2017). Influence of elevated soil temperature and biochar application on organic matter associated with aggregate-size and density fractions in an arable soil. *Agriculture, Ecosystems & Environment*, *241*, 79–87.

Hammond, J., Shackley, S., Sohi, S., & Brownsort, P. (2011). Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. *Energy Policy*, *39*(5), 2646–2655. https://doi.org/10.1016/j.enpol.2011.02.033

Hanak, E., Escriva-Bou, A., Gray, B., Green, S., Harter, T., Jezdimirovic, J., Lund, J., Medellín-Azuara, J., Moyle, P., & Seavy, N. (2019). Water and the future of the San Joaquin Valley. *Public Policy Institute of California*, *100*.

Harrison, B. P., Gao, S., Gonzales, M., Thao, T., Bischak, E., Ghezzehei, T. A., Berhe, A. A., Diaz, G., & Ryals, R. A. (2022). Dairy Manure Co-composting with Wood Biochar Plays a Critical Role in Meeting Global Methane Goals. *Environmental Science & Technology*, *56*(15), 10987–10996. https://doi.org/10.1021/acs.est.2c03467

Harrison, M. (2010). Valuing the Future: the social discount rate in cost-benefit analysis. *Available at SSRN 1599963*.

Hašková, S. (2017). Holistic assessment and ethical disputation on a new trend in solid biofuels. *Science and Engineering Ethics*, *23*(2), 509–519.

He, L., English, B. C., Menard, R. J., & Lambert, D. M. (2016). Regional woody biomass supply and economic impacts from harvesting in the southern US. *Energy Economics*, *60*, 151–161.

Hoel, M., & Sterner, T. (2007). Discounting and relative prices. *Climatic Change*, *84*(3–4), 265–280.

Hou, L., Keske, C., Hoag, D., Balezentis, T., & Wang, X. (2019). Abatement costs of emissions from burning maize straw in major maize regions of China: Balancing food security with the environment. *Journal of Cleaner Production*, *208*, 178–187. https://doi.org/10.1016/j.jclepro.2018.10.047

Hultkrantz, L., Krüger, N. A., & Mantalos, P. (2014). Risk-adjusted long-term social rates of discount for transportation infrastructure investment. *Research in Transportation Economics*, *47*, 70–81.

Hunt, J., DuPonte, M., Sato, D., & Kawabata, A. (2010). The basics of biochar: A natural soil amendment. *Soil and Crop Management*, *30*(7), 1–6.

IMPLAN. (2022). *Economic input-output modeling application, data, and solutions.*

Institute for European Environmental Policy. (2018). *Promoting a circular, sustainable bioeconomy – delivering the bioeconomy society needs.* https://ieep.eu/news/promoting-a-circular-sustainable-bioeconomy-delivering-the-bioeconomy-society-needs (accessed 15 June 2021).

Intergovernmental Panel on Climate Change. (2007). *Climate Change 2007 - Mitigation of Climate Change: Working Group III contribution to the Fourth Assessment*

*Report of the IPCC*. Cambridge University Press. https://doi.org/10.1017/CBO9780511546013.

IPCC. (2013). *The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Jackson, R. W., Borges Ferreira Neto, A., Erfanian, E., & Járosi, P. (2019). Woody biomass processing and rural regional development. *Economic Development Quarterly*, *33*(3), 234–247.

Jackson, R. W., Neto, A. B. F., & Erfanian, E. (2018). Woody biomass processing: Potential economic impacts on rural regions. *Energy Policy*, *115*, 66–77. https://doi.org/10.1016/j.enpol.2018.01.001

Jia, X., Yuan, W., & Ju, X. (2015). Effects of Biochar Addition on Manure Composting and Associated N 2 O Emissions. *Journal of Sustainable Bioenergy Systems*, *5*(02), 56.

Joshi, O., Grebner, D. L., Henderson, J. E., Grado, S. C., & Munn, I. A. (2012). Input–output modeling of wood-based bioenergy industries in Mississippi. *Forest Products Journal*, *62*(7–8), 528–537.

Kaffka, S., Williams, R. B., & Wickizer, D. (2013). *Biomass Energy in California's Future: Barriers, Opportunities, and Research Needs - Draft Report*.

Karhu, K., Mattila, T., Bergström, I., & Regina, K. (2011). Biochar addition to agricultural soil increased CH4 uptake and water holding capacity – Results from a short-term pilot field study. *Agriculture, Ecosystems & Environment*, *140*(1), 309–313. https://doi.org/10.1016/j.agee.2010.12.005

Karp, L., & Traeger, C. (2013). Discounting. In J. F. Shogren (Ed.), *Encyclopedia of Energy, Natural Resource, and Environmental Economics* (pp. 286–292). Elsevier. https://doi.org/10.1016/B978-0-12-375067-9.00150-9

Keske, C. (2020). *Up in the air: will California's methane gas mitigation laws and policies lower global greenhouse gas emissions?*

Keske, C., Godfrey, T., Hoag, D. L. K., & Abedin, J. (2019). Economic feasibility of biochar and agriculture coproduction from Canadian black spruce forest. *Food and Energy Security*, *September*, 1–11. https://doi.org/10.1002/fes3.188

Keske, C., Mills, M., Tanguay, L., & Dicker, J. (2018). Waste Management in Labrador and Northern Communities: Opportunities and Challenges. *The Northern Review*, *47*, 79–112. https://doi.org/10.22584/nr47.2018.005

Kim, D., Anderson, N. M., & Chung, W. (2015). Financial performance of a mobile pyrolysis system used to produce biochar from sawmill residues. *Forest Products Journal*, *65*(5–6), 189–197.

Kourmentza, C., Economou, C. N., Tsafrakidou, P., & Kornaros, M. (2018). Spent coffee grounds make much more than waste: Exploring recent advances and future exploitation strategies for the valorization of an emerging food waste stream. *Journal of Cleaner Production*, *172*, 980–992.

Krüger, N. A. (2012). Estimating traffic demand risk–a multiscale analysis. *Transportation Research Part A: Policy and Practice*, *46*(10), 1741–1751.

Kung, K. S., Shanbhogue, S., Slocum, A. H., & Ghoniem, A. F. (2019). A decentralized biomass torrefaction reactor concept. Part I: Multi-scale analysis and initial experimental validation. *Biomass and Bioenergy*, *125*, 196–203. https://doi.org/10.1016/j.biombioe.2018.11.004

Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, *3*(5), 547–562.

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, *31*(4), 575–584. https://doi.org/10.1016/j.envint.2004.09.005

Lan, R., Eastham, S. D., Liu, T., Norford, L. K., & Barrett, S. R. H. (2022). Air quality impacts of crop residue burning in India and mitigation alternatives. *Nature Communications*, *13*(1), 6537.

Larson, R. W. (2008). Using biochar for cost-effective CO 2 sequestration in soils. *Proceedings of ISES World Congress 2007 (Vol. I–Vol. V)*, 2462–2467.

Latawiec, A. E., Koryś, A., Koryś, K. A., Kuboń, M., Sadowska, U., Gliniak, M., Sikora, J., Drosik, A., Niemiec, M., & Klimek-Kopyra, A. (2021). Economic analysis of biochar use in soybean production in Poland. *Agronomy*, *11*(11), 2108.

Lee, J.-C., Lee, B., Ok, Y. S., & Lim, H. (2020). Preliminary techno-economic analysis of biodiesel production over solid-biochar. *Bioresource Technology*, *306*, 123086. https://doi.org/10.1016/j.biortech.2020.123086

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, *43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Lehmann, J., & Rondon, M. (2006). Bio-char soil management on highly weathered soils in the humid tropics. *Biological Approaches to Sustainable Soil Systems*, *113*(517), e530.

Li, C., Bair, D. A., & Parikh, S. J. (2018). Estimating potential dust emissions from biochar amended soils under simulated tillage. *Science of the Total Environment*, *625*, 1093–1101.

Li, W., Dang, Q., Brown, R. C., Laird, D., & Wright, M. M. (2017). The impacts of biomass properties on pyrolysis yields, economic and environmental performance of the pyrolysis-bioenergy-biochar platform to carbon negative energy. *Bioresource Technology*, *241*(September), 959–968. https://doi.org/https://doi.org/10.1016/j.biortech.2017.06.049

Lintner, J. (1965a). Security Prices, Risk, and Maximal Gains From Diversification. *The Journal of Finance*, *20*(4), 587–615. https://doi.org/10.2307/2977249

Lintner, J. (1965b). The Valuation of Risk Assets and the Selection of Risky Investments in Stock Portfolios and Capital Budgets. *The Review of Economics and Statistics*, *47*(1), 13–37. https://doi.org/10.2307/1924119

Liu, W., Huo, R., Xu, J., Liang, S., Li, J., Zhao, T., & Wang, S. (2017). Effects of biochar on nitrogen transformation and heavy metals in sludge composting. *Bioresource Technology*, *235*, 43–49.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., & Paz-Ferreiro, J. (2013). Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. *Plant and Soil*, *373*(1–2), 583–594. https://doi.org/10.1007/s11104-013-1806-x

Lu, S.-G., Sun, F.-F., & Zong, Y.-T. (2014). Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (Vertisol). *Catena*, *114*, 37–44.

Lucas Jr, R. E. (1978). Asset prices in an exchange economy. *Econometrica: Journal of the Econometric Society*, 1429–1445.

Mahdi, M. A., Yousefi, S. R., Jasim, L. S., & Salavati-Niasari, M. (2022). Green synthesis of DyBa2Fe3O7. 988/DyFeO3 nanocomposites using almond extract with dual eco-friendly applications: photocatalytic and antibacterial activities. *International Journal of Hydrogen Energy*, *47*(31), 14319–14330.

Major, J. (2011). Biochar: A new soil management tool for farmers and gardeners. *Appalachian Sustainable Development*.

Mardoyan, A., & Braun, P. (2015). Analysis of Czech subsidies for solid biofuels. *International Journal of Green Energy*, *12*(4), 405–408.

Maroušek, J., Maroušková, A., & Kůs, T. (2020). Shower cooler reduces pollutants release in production of competitive cement substitute at low cost. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–10.

Maroušek, J., Stehel, V., Vochozka, M., Maroušková, A., & Kolář, L. (2018). Postponing of the intracellular disintegration step improves efficiency of phytomass processing. *Journal of Cleaner Production*, *199*, 173–176.

Maroušek, J., Strunecký, O., & Stehel, V. (2019). Biochar farming: Defining economically perspective applications. *Clean Technologies and Environmental Policy*, *21*(7), 1389–1395.

Mayhead, G., & Tittmann, P. (2012). Uncertain future for California's biomass power plants. *California Agriculture*, *66*(1), 6.

McCarty, J. L., Korontzi, S., Justice, C. O., & Loboda, T. (2009). The spatial and temporal distribution of crop residue burning in the contiguous United States. *Science of The Total Environment*, *407*(21), 5701–5712. https://doi.org/10.1016/j.scitotenv.2009.07.009

Meyer, S., Genesio, L., Vogel, I., Schmidt, H.-P., Soja, G., Someus, E., Shackley, S., Verheijen, F. G. A., & Glaser, B. (2017). Biochar standardization and legislation harmonization. *Journal of Environmental Engineering and Landscape Management*, *25*(2), 175–191.

Michaud, G., & Jolley, G. J. (2019). Economic contribution of Ohio's wood industry cluster: identifying opportunities in the Appalachian region. *Review of Regional Studies*, *49*(1), 149–171.

Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: foundations and extensions*. Cambridge university press.

Miyata, E. S. (1980). Determining fixed and operating costs of logging equipment. *General Technical Report NC-55*, 1–20.

Mohammadi, A., Cowie, A. L., Cacho, O., Kristiansen, P., Anh Mai, T. L., & Joseph, S. (2017). Biochar addition in rice farming systems: Economic and energy benefits. *Energy*, *140*, 415–425. https://doi.org/10.1016/j.energy.2017.08.116

Mohammed, N. I., Kabbashi, N., & Alade, A. (2018). Significance of Agricultural Residues in Sustainable Biofuel Development. *Agricultural Waste and Residues*, 71.

Mohan, D., Abhishek, K., Sarswat, A., Patel, M., Singh, P., & Pittman, C. U. (2018). Biochar production and applications in soil fertility and carbon sequestration–a sustainable solution to crop-residue burning in India. *RSC Advances*, *8*(1), 508–520.

Moore, M. A., Boardman, A. E., & Vining, A. R. (2013). More appropriate discounting: the rate of social time preference and the value of the social discount rate. *Journal of Benefit-Cost Analysis*, *4*(1), 1–16.

Moore, M., & Vining, A. (2018). The social rate of time preference and the social discount rate. *Mercatus Research Paper, December*.

Mossin, J. (1966). Equilibrium in a capital asset market. *Econometrica: Journal of the Econometric Society*, 768–783.

Muñoz Torrecillas, M. J., Roche, J., & Cruz Rambaud, S. (2019). Building a social discount rate to be applied in US afforestation project appraisal. *Forests*, *10*(5), 445.

Mutton Power Equipment. (2020). *Frontier AP12F Pallet Forks for John Deere*. https://www.muttonpower.com/product/9561/frontier-fixed-pallet-forks-ap12f (accessed March 2020).

Naeem, I., Masood, N., Turan, V., & Iqbal, M. (2021). Prospective usage of magnesium potassium phosphate cement combined with Bougainvillea alba derived biochar to reduce Pb bioavailability in soil and its uptake by Spinacia oleracea L. *Ecotoxicology and Environmental Safety*, *208*, 111723.

Nefzi, N. (2018). Fear of failure and entrepreneurial risk perception. *International Journal of Entrepreneurial Knowledge*, *6*(2), 45–58.

Nematian, M., Keske, C., & Ng'ombe, J. N. (2021). A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. *Waste Management, 135*, 467–477. https://doi.org/10.1016/j.wasman.2021.09.014

Ng, W. C., You, S., Ling, R., Gin, K. Y.-H., Dai, Y., & Wang, C.-H. (2017). Co-gasification of woody biomass and chicken manure: Syngas production, biochar reutilization, and cost-benefit analysis. *Energy*, *139*, 732–742.

Nordhaus, W. D. (2007). A review of the Stern review on the economics of climate change. *Journal of Economic Literature*, *45*(3), 686–702.

Ogbonnaya, U., & Semple, K. T. (2013). Impact of biochar on organic contaminants in soil: a tool for mitigating risk? *Agronomy*, *3*(2), 349–375.

Olarieta, J. R., Padrò, R., Masip, G., Rodríguez-Ochoa, R., & Tello, E. (2011). 'Formiguers', a historical system of soil fertilization (and biochar production?). *Agriculture, Ecosystems & Environment*, *140*(1–2), 27–33.

Olson, D., & Lindall, S. (1996). IMPLAN professional software, analysis, and data guide: Minnesota IMPLAN Group. *Inc., Stillwater, Minnesota*.

Palansooriya, K. N., Ok, Y. S., Awad, Y. M., Lee, S. S., Sung, J.-K., Koutsospyros, A., & Moon, D. H. (2019). Impacts of biochar application on upland agriculture: A review. *Journal of Environmental Management*, *234*, 52–64. https://doi.org/10.1016/j.jenvman.2018.12.085

Palisade. (2019). *Industrial Software, Palisade Software* (7.6).

Peiris, C., Gunatilake, S. R., Mlsna, T. E., Mohan, D., & Vithanage, M. (2017). Biochar based removal of antibiotic sulfonamides and tetracyclines in aquatic environments: a critical review. *Bioresource Technology*, *246*, 150–159.

Perez-Verdin, G., Grebner, D. L., Munn, I. A., Sun, C., & Grado, S. C. (2008). Economic impacts of woody biomass utilization for bioenergy in Mississippi. *Forest Products Journal*, *58*(11), 75–83.

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. https://doi.org/10.1021/es5060786

Petter, R., & Tyner, W. E. (2014). Technoeconomic and policy analysis for corn stover biofuels. *International Scholarly Research Notices*, *2014*.

Polasky, S., & Dampha, N. K. (2021). Discounting and global environmental change. *Annual Review of Environment and Resources*, *46*, 691–717.

Poudineh, R. (2020). *Social discount rate and the energy transition policy*.

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.

Pratt, K., & Moran, D. (2010). Evaluating the cost-effectiveness of global biochar mitigation potential. *Biomass and Bioenergy*, *34*(8), 1149–1158. https://doi.org/10.1016/j.biombioe.2010.03.004

Propst, D. B., & Gavrilis, D. G. (1987). Role of economic impact assessment procedures in recreational fisheries management. *Transactions of the American Fisheries Society*, *116*(3), 450–460.

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. In *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2017.05.057

Ramsey, F. P. (1928). A mathematical theory of saving. *The Economic Journal*, *38*(152), 543–559.

Rasool, B., Zubair, M., Khan, M. A., Ramzani, P. M. A., Dradrach, A., Turan, V., Iqbal, M., Khan, S. A., Tauqeer, H. M., & Farhad, M. (2022). Synergetic efficacy of amending Pb-polluted soil with P-loaded jujube (Ziziphus mauritiana) twigs biochar and foliar chitosan application for reducing Pb distribution in moringa leaf extract and improving its anti-cancer potential. *Water, Air, & Soil Pollution*, *233*(8), 344.

Rathore, A. S., & Singh, A. (2022). Biomass to fuels and chemicals: A review of enabling processes and technologies. *Journal of Chemical Technology & Biotechnology*, *97*(3), 597–607.

Raza, M. H., Abid, M., Yan, T., Naqvi, S. A. A., Akhtar, S., & Faisal, M. (2019). Understanding farmers' intentions to adopt sustainable crop residue management practices: A structural equation modeling approach. *Journal of Cleaner Production*, *227*, 613–623.

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. https://doi.org/10.1021/es902266r

Romasanta, R. R., Sander, B. O., Gaihre, Y. K., Alberto, Ma. C., Gummert, M., Quilty, J., Nguyen, V. H., Castalone, A. G., Balingbing, C., Sandro, J., Correa, T., & Wassmann, R. (2017). How does burning of rice straw affect CH4 and N2O emissions? A comparative experiment of different on-field straw management practices. *Agriculture, Ecosystems & Environment*, *239*, 143–153. https://doi.org/10.1016/j.agee.2016.12.042

Rosen, H. S. (2004). Public finance. In *The encyclopedia of public choice* (pp. 252–262). Springer.

Rotochopper Inc. (2020). *Rotochopper Go-Bagger® 250 Portable Bagging System*. https://www.rotochopper.com/product/gb-250/ (accessed March 2020).

Rubinstein, M. (1976). The valuation of uncertain income streams and the pricing of options. *The Bell Journal of Economics*, 407–425.

Sabalow. (2021). *California air board OKs crackdown on agricultural burning in San Joaquin Valley*. https://www.fresnobee.com/news/business/agriculture/article249514990.html

Sadaka, S., Sharara, M. A., Ashworth, A., Keyser, P., Allen, F., & Wright, A. (2014). Characterization of biochar from switchgrass carbonization. *Energies*, *7*(2), 548–567.

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*(July 2018), 578–590. https://doi.org/10.1016/j.apenergy.2018.10.076

Scarborough, H. (2011). Intergenerational equity and the social discount rate. *Australian Journal of Agricultural and Resource Economics*, *55*(2), 145–158.

Schmit, T., Jablonski, B., & Kay, D. (2013). A practitioner's guide to conducting an economic impact assessment of regional food hubs using IMPLAN: A step-by-step approach. *Cornell Univ https://apps.ams.usda.gov/MarketingPublicationSearch/Reports/stelprdc5110439.pdf (accessed 17 July 2022).*

Shabangu, S., Woolf, D., Fisher, E. M., Angenent, L. T., & Lehmann, J. (2014). Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts. *Fuel*, *117*, 742–748. https://doi.org/10.1016/j.fuel.2013.08.053

Shackley, S., Hammond, J., Gaunt, J., & Ibarrola, R. (2011). The feasibility and costs of biochar deployment in the UK. *Carbon Management*, *2*(3), 335–356.

Shahbaz, A. K., Ramzani, P. M. A., Saeed, R., Turan, V., Iqbal, M., Lewińska, K., Abbas, F., Saqib, M., Tauqeer, H. M., & Iqbal, M. (2019). Effects of biochar and zeolite soil amendments with foliar proline spray on nickel immobilization, nutritional quality and nickel concentrations in wheat. *Ecotoxicology and Environmental Safety*, *173*, 182–191.

Shamim, M. I. A., Uddin, N., Hossain, S. A. A. M., Ruhul, A., & HIEMSTRA, T. (2015). Production of biochar for soil application: a comparative study of three kiln models. *Pedosphere*, *25*(5), 696–702.

Sharpe, W. F. (1964). Capital asset prices: A theory of market equilibrium under conditions of risk. *The Journal of Finance*, *19*(3), 425–442.

Skapa, S. (2012). Investment characteristics of natural monopoly companies. *Journal of Competitiveness*, *4*(1).

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. B. T.-A. in A. (2010). Chapter 2 - A Review of Biochar and Its Use and Function in Soil. In *Advances in Agronomy* (Vol. 105, pp. 47–82). Academic Press. https://doi.org/10.1016/S0065-2113(10)05002-9

Spokas, K. A., & Reicosky, D. C. (2009). *Impacts of sixteen different biochars on soil greenhouse gas production*.

Springsteen, B., Christofk, T., Eubanks, S., Mason, T., Clavin, C., & Storey, B. (2011). Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning. *Journal of the Air & Waste Management Association*, *61*(1), 63–68. https://doi.org/10.3155/1047-3289.61.1.63

State of California. (2020). *CalCareers*. https://www.jobs.ca.gov/CalHRPublic/Search/JobSearchResults.aspx#kw=Agriculture&socmajorcode=45-0000 (accessed March 2020).

Stein, W. E., & Keblis, M. F. (2009). A new method to simulate the triangular distribution. *Mathematical and Computer Modelling*, *49*(5–6), 1143–1147. https://doi.org/10.1016/j.mcm.2008.06.013

Steinback, S. R. (1999). Regional economic impact assessments of recreational fisheries: an application of the IMPLAN modeling system to marine party and charter boat fishing in Maine. *North American Journal of Fisheries Management*, *19*(3), 724–736.

Steiner, C., Teixeira, W. G., & Zech, W. (2004). Slash and char: an alternative to slash and burn practiced in the Amazon basin. *Amazonian Dark Earths: Explorations in Space and Time*, 183–193.

Stern, N. (2007). *The economics of climate change: the Stern review*. cambridge University press.

Sterner, T., & Persson, U. M. (2008). An even sterner review: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy*.

Tauqeer, H. M., Basharat, Z., Ramzani, P. M. A., Farhad, M., Lewińska, K., Turan, V., Karczewska, A., Khan, S. A., Faran, G., & Iqbal, M. (2022). Aspergillus nigermediated release of phosphates from fish bone char reduces Pb phytoavailability in Pb-acid batteries polluted soil, and accumulation in fenugreek. *Environmental Pollution*, *313,* 120064.

Tauqeer, H. M., Fatima, M., Rashid, A., Shahbaz, A. K., Ramzani, P. M. A., Farhad, M., Basharat, Z., Turan, V., & Iqbal, M. (2021). The current scenario and prospects of immobilization remediation technique for the management of heavy metals contaminated soils. *Approaches to the Remediation of Inorganic Pollutants*, 155–185.

Tenenbaum, D. J. (2009). *Biochar: carbon mitigation from the ground up*. National Institute of Environmental Health Sciences.

Thengane, S. K., Kung, K., York, R., Sokhansanj, S., Lim, C. J., & Sanchez, D. L. (2020). Technoeconomic and emissions evaluation of mobile in-woods biochar production. *Energy Conversion and Management*, *223,* 113305.

Timmons, D. S., Allen, P. G., Damery, D., Petraglia, L. M., & Group, E. D. R. (2007). *Energy from forest biomass: Potential economic impacts in Massachusetts*. Citeseer.

Title 17 of the California Code of Regulations. (2001). Title 17 of the California Code of Regulations, 2001. Subchapter 2. Smoke Management Guidelines for Agricultural and Prescribed Burning. https://ww3.arb.ca.gov/smp/regs/revfinregwtoc.pdf (accessed 10 January 2021).

Treasury, H. M. (2003). The green book. *Appraisal and Evaluation in Central Government*.

Treynor, J. L. (1961). *Toward a theory of market value of risky assets*.

Turan, V., Ramzani, P. M. A., Ali, Q., Abbas, F., Iqbal, M., Irum, A., & Khan, W.-D. (2018). Alleviation of nickel toxicity and an improvement in zinc bioavailability in sunflower seed with chitosan and biochar application in pH adjusted nickel contaminated soil. *Archives of Agronomy and Soil Science*, *64*(8), 1053–1067.

Urbancova, H. (2013). Competitive advantage achievement through innovation and knowledge. *Journal of Competitiveness*, *5*(1).

U.S. Bureau of Economic Analysis. (2023). *Real personal consumption expenditures per capita [A794RX0Q048SBEA], retrieved from FRED, Federal Reserve Bank of St. Louis*. https://fred.stlouisfed.org/series/A794RX0Q048SBEA (accessed Nov 2023).

U.S. Energy Information Administration. (2021). *Gasoline and Diesel Fuel Update*. https://www.eia.gov/petroleum/gasdiesel/ (accessed June 2021).

U.S. Environmental Protection Agency. (2023a). *EJScreen: Environmental Justice Screening and Mapping Tool*. https://www.epa.gov/ejscreen (accessed Nov 2023).

U.S. Environmental Protection Agency. (2023b). *Particulate Matter (PM) Pollution*. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#PM (accessed Nov 2023).

U.S. Environmental Protection Agency (EPA). (2019). *EJSCREEN Technical Documentation.* https://www.epa.gov/sites/default/files/2017-09/documents/2017_ejscreen_technical_document.pdf (accessed Nov 2023).

U.S. Environmental Protection Agency (EPA). (2023, June 26). *EJ and Supplemental Indexes in EJScreen*. https://www.epa.gov/ejscreen/ej-and-supplemental-indexes-ejscreen (accessed Nov 2023).

U.S. Farm Bill. (2008). *Food, Conservation, and Energy Act of 2008. U.S. 110th Congress. H.R. 6124. Public Law No: 110–246.* https://www.congress.gov/bill/110th-congress/house-bill/6124 (accessed 10 January 2021).

U.S. Farm Bill. (2014). *Agricultural Act of 2014. U.S. 113th Congress. H.R.2642. Public Law No: 113–79*. https://www.congress.gov/bill/113th-congress/house-bill/2642 (accessed 10 January 2021).

USDA NASS. (2021). *2020 California Almond Acreage Report* (Vol. 95812, Issue 916). https://www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Almond/Acreage/202104_almac.pdf (accessed 10 January 2021).

USDA NRCS. (2019). *Interim Conservation Practice Standard Soil Carbon Amendment Code 808*. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5e429f851f12287bd48c8e1a/1581424518098/CPS_808_SoilCarbonAmendment_Interim.pdf (accessed 10 January 2021).

USDA-RD. (2015). *Biorefinery, renewable chemical, and biobased product manufacturing assistance program. Rural Development, United States Department of Agriculture*. https://www.rd.usda.gov/programs-services/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance (accessed 10 January 2021).

van Ewijk, C., & Tang, P. J. G. (2003). Notes and Communications: How to price the risk of public investment? *De Economist*, *151*(3), 317.

Vochozka, M., Maroušková, A., Váchal, J., & Straková, J. (2016). Biochar pricing hampers biochar farming. *Clean Technologies and Environmental Policy*, *18*(4), 1225–1231.

Vogel, D. (2019). *California greenin': How the Golden State became an environmental leader* (Vol. 162). Princeton University Press.

Weikard, H.-P., & Zhu, X. (2005). Discounting and environmental quality: when should dual rates be used? *Economic Modelling*, *22*(5), 868–878.

Weitzman, M. L. (2001). Gamma Discounting. *American Economic Review*, *91*(1), 260–271. https://doi.org/10.1257/aer.91.1.260

Weitzman, M. L. (2007). A review of the Stern Review on the economics of climate change. *Journal of Economic Literature*, *45*(3), 703–724.

Weitzman, M. L. (2013). Tail-Hedge Discounting and the Social Cost of Carbon. *Journal of Economic Literature*, *51*(3), 873–882. http://www.jstor.org/stable/23644837

Winton Hardware. (2020). *MS 880 MAGNUM® Chainsaw in Winton, CA 95388*. https://wintonhardware.stihldealer.net/products/chain-saws/professional-saws/ms880/ (accessed March 2020).

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. https://doi.org/10.1016/j.biombioe.2015.06.015

Wu, H., Lai, C., Zeng, G., Liang, J., Chen, J., Xu, J., Dai, J., Li, X., Liu, J., & Chen, M. (2017). The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review. *Critical Reviews in Biotechnology*, *37*(6), 754–764.

Xiang, L., Liu, S., Ye, S., Yang, H., Song, B., Qin, F., Shen, M., Tan, C., Zeng, G., & Tan, X. (2021). Potential hazards of biochar: The negative environmental impacts of biochar applications. *Journal of Hazardous Materials*, *420*, 126611.

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.

Yousefi, S. R., Alshamsi, H. A., Amiri, O., & Salavati-Niasari, M. (2021). Synthesis, characterization and application of Co/Co3O4 nanocomposites as an effective photocatalyst for discoloration of organic dye contaminants in wastewater and antibacterial properties. *Journal of Molecular Liquids*, *337*, 116405.

Zafar, S., Khan, I. M., Muddasar, M., Iqbal, R., Bashir, T., Shahzad, A., Bashir, S., & Shah, A. A. (2023). Biochar Application to Soil to Improve Fertility. In *Sustainable Agriculture Reviews 61: Biochar to Improve Crop Production and Decrease Plant Stress under a Changing Climate* (pp. 99–120). Springer.

Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., Zheng, J., & Crowley, D. (2010). Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems & Environment*, *139*(4), 469–475. https://doi.org/10.1016/j.agee.2010.09.003

Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L., Zheng, J., & Zhang, X. (2012). Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. *Plant and Soil*, *351*(1), 263–275. https://doi.org/10.1007/s11104-011-0957-x

Zhuang, J., Liang, Z., Lin, T., & De Guzman, F. (2007). *Theory and practice in the choice of social discount rate for cost-benefit analysis: a survey*. ERD working paper series.

Zubair, M., Ramzani, P. M. A., Rasool, B., Khan, M. A., Akhtar, I., Turan, V., Tauqeer, H. M., Farhad, M., Khan, S. A., & Iqbal, J. (2021). Efficacy of chitosan-coated textile waste biochar applied to Cd-polluted soil for reducing Cd mobility in soil and its distribution in moringa (Moringa oleifera L.). *Journal of Environmental Management, 284*, 112047.