BIOCHAR CARBON CREDIT MARKET ANALYSIS

Examining the potential for coupled biochar and carbon credit production from wildfire fuel reduction projects in the Western U.S.

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Cover Photo: Belted trailer unloads biochar at West Marin Compost, Nicasio, CA. (Josiah Hunt, Pacific Biochar)

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Executive Summary

This report evaluates the potential to utilize low-value or non-merchantable woody biomass generated from forest thinning and restoration projects to jointly produce biochar products and carbon credits. While biochar can be produced from many feedstocks, biochar produced from woody biomass has the potential to contribute to much-needed forest restoration throughout the Western U.S. while providing a source of carbon credits perceived as high quality by carbon offset purchasers.

Biochar has emerged as a climate beneficial and productive use of the enormous amounts of woody biomass generated during forest restoration and fuel thinning projects throughout the Western U.S. Throughout the Western U.S., between 4 and 18 million tonnes of non-merchantable woody biomass are produced from forest restoration projects annually. That biomass could create between 1 and 4 million tonnes of biochar and 2 to 11 million carbon credits. These numbers may increase up to 25 times if various state and federal forest management goals are met.

Co-production of biochar and carbon credits can provide high quality carbon offsets and large quantities of biochar through several production strategies. Current biochar production in California is less than 10,000 tonnes per year and less than 20,000 tonnes per year throughout the West, although specific numbers are challenging given the lack of transparency in the market. Roughly 42,000 tonnes of biochar could be produced with modest upgrades to a portion of the biopower facilities in California and 69,000 tonnes of biochar with upgrades throughout the West. Approximately 210,000 tonnes of biochar could be produced with more intensive upgrades to the California biopower facilities and 340,000 tonnes with upgrades to facilities throughout the West. This corresponds to potential carbon credit generation of up to 570,000 credits per year in California and 930,000 credits annually throughout the West.

Carbon credit prices are critical to sustained industry growth. The hypothesized demand from market experts for carbon credits from biochar is high and not a limiting factor in the near term. We expect voluntary carbon offsets will sustain current prices around $100 as long as biochar credits remain niche and marketed at buyers concerned with durability and quality. However, for biochar credits to be transacted in volumes at a scale in the hundreds of thousands of tonnes per year, biochar carbon offset prices may need to drop lower than they are today.

Agricultural soil amendments provide potential for biochar end use markets. Biochar applications can provide economic returns in as little as two harvests. Throughout the U.S., the potential market for biochar soil applications is over three billion tonnes. We conducted a discounted cost flow analysis to investigate the potential for biochar applications to improve economic returns in agriculture. Assuming a 10% yield increase, we find that high value crops benefit greatly from biochar applications at $240 per tonne biochar and with four tonnes applied per acre every five years. Pistachios in particular stand out, with a positive return after the second harvest and an additional value of $239 added per tonne of biochar applied.

Our examination of the financial viability of four biochar production systems finds that all production systems have positive Internal Rates of Return and Net Present Values in certain scenarios. We model the profitability of four different biochar production facilities with a discounted cash flow analysis under the following market scenarios: a 25MW biopower facility with both light and heavy upgrades, a mobile biochar unit, and dedicated centralized biochar production. The market scenarios modeled include the effects of biochar pricing between $100-250 per ton, carbon pricing between $0-100 per tonne CO_2, and feedstock costs between $0-120 per tonne. **The light upgrade of the biopower facilities has the highest returns, with Internal Rates of Return generally between 10-30%, although each production system had positive returns in certain scenarios. Production types with lower returns may still provide opportunities for landowners to defray costs associated with dealing with non-merchantable biomass, potentially cutting those costs in half.**

$100 million in investments could generate up to four million carbon credits over 10 years and investments between $20 - 50 billion could utilize all of the non-merchantable forest biomass generated from forest restoration, roughly 100 million tonnes annually throughout the West assuming an increased forest management scenario. The various production systems examined in this report may be better suited to different types of investment or financing (equity, debt, or public subsidies), but the total investment potential is large.

Large scale utilization of non-merchantable forest biomass as a feedstock for biochar production will be made possible by transparent and consistent feedstock supply chains coupled with 1) high carbon market prices, 2) a subsidy or other price mechanism to lower feedstock costs, or 3) economies of scale. Increasing attention, investment, and collaboration in the biochar space, alongside the immediate need for high quality carbon credits, may help overcome historical barriers to the biochar industry.

1. Introduction

Biochar can be made from a range of biomass materials - such as woody biomass from forest restoration projects, food and yard waste, and crop residues - and has promising applications in agriculture, forestry, and other industries. This report explores the potential for generating carbon credits alongside biochar particularly from woody biomass generated during forest restoration and thinning projects throughout the Western United States, with a particular focus on California. The biochar market throughout the United States has recently begun to grow, but sales are still limited primarily by lack of demand, access to capital, and other market barriers (Thengane, Kung, Hunt, et al. 2021). However, biochar has gained increased attention in the academic literature in recent years for its potential to retain soil moisture and nutrients while improving soil quality and storing carbon (H. Schmidt et al. 2021). Coupling the production of biochar with carbon offset credit generation provides an opportunity to foster an industry with potential for local ecological impacts and global climate benefits, while improving profitability of biochar production. To date, the large majority of biochar producers have utilized either agricultural waste or sawmill residues to produce biochar given the relatively cheaper feedstock prices and lack of supply chain and sourcing challenges.

In California, 90% of the largest and most destructive fires in recorded history have occurred since 2010 (CalFire 2021), with similar trends throughout the Western U.S. The increasing severity of wildfires throughout the state has been caused by a combination of management decisions exacerbated by climate change. To address this risk while restoring ecosystem health to forests throughout the state, enormous amounts of woody biomass need to be removed (Collins, Everett, and Stephens 2011; Lydersen and Collins 2018; McIntyre et al. 2015). The State of California and the U.S. Department of Agriculture, Forest Service have goals to collectively reduce fire risk on one million acres of forest land per year, representing roughly a fourfold increase in acres treated (USDA Forest Service Pacific Southwest Region 2020). Biomass generated from forest treatment is often non-merchantable and is generally piled and burned, with little going to productive uses or generating revenue. Pile burning biomass not only releases stored carbon but represents high costs to land managers. The anticipated increase in treatment efforts creates an opportunity for innovative wood products such as biochar.

Although biochar production can utilize a range of different feedstocks, the increase in forest management throughout the state offers a unique opportunity to produce biochar and carbon credits while providing a climate beneficial use for the flow of biomass from forest restoration projects. With the goal of understanding the potential for coupling forest restoration with biochar and carbon credit production, we investigate several questions:

1. **What is the potential supply of woody biomass from forest restoration projects throughout California and the Western United States?**
2. **What is the current generation capacity for coupled biochar and carbon offset production in California? What is the potential capacity if biopower facilities throughout the state were upgraded to produce biochar? How many carbon credits could be generated given different production scenarios?**
3. **What is the potential demand for carbon credits coupled with biochar production?**
4. **What is the potential demand and financial impact of biochar used as an agricultural soil amendment?**
5. **What is the financial viability of different biochar production systems? How do fluctuations in carbon credit price, biochar price, and feedstock costs affect viability?**
6. **What is the potential for investment in biochar production?**

The findings from this report can be used as a starting place to guide investment in the biochar industry while providing an understanding of the feasibility of using woody biomass from forest restoration projects to create biochar and carbon credits.

2. Annual Woody Biomass Supply and Potential for Coupled Biochar and Carbon Credit Production

Large volumes of non-merchantable woody biomass are typically left in the forest after restoration and fuel thinning projects, with much of that material being piled and burned, releasing the stored carbon, and presenting higher management costs to land owners (Springsteen et al. 2015). As the pace and scale of forest restoration increase to meet state and federal goals, the potential supply of this biomass will greatly increase. The amount of biomass remaining in the forest after restoration will vary by site given a range of factors, including local wood product markets, diameter of trees removed, and management objectives. With these shifting dynamics in mind, we estimated both the current amount of biomass left in the forest in the form of slash as a byproduct of restoration and the future amount of slash given expected increases in forest restoration. We further translated these forest slash estimates into the potential amount of biochar and carbon credits which can be made from this biomass without considering the limitation of current biochar production capacity (see Table 1).

Table 1: Annual Woody Biomass Supply and Potential Coupled Biochar and Carbon Credit Production

	Biomass Supply (Million Tonnes)		Potential Biochar (Million Tonnes)		Potential Carbon Credits (Millions)	
California	Low	High	Low	High	Low	High
Current (approx. 250,000 acres treated)	1	5	0.25	1.3	0.5	3.5
Increased Forest Management (500,000 - 1,000,000 acres treated)	8	22	2	5.5	4	15
Western U.S.						
Current (approx. 1,500,000 acres treated)	4	18	1	4	2	11
Increased Forest Management (2,000,000 - 4,000,000) acres treated	24	102	6	26	11	69

We model the current technical supply of non-merchantable forest biomass based on several key factors including 1) the number of acres of forest land treated, 2) the amount of biomass harvested during fuel thinning projects, 3) the proportion of the harvest which is currently left in the forest as slash, and 4) the current and increased capacity of the wood products infrastructure in California and the West. A key assumption in the supply of non-merchantable forest biomass moving forward is the capacity of sawmills and other traditional wood products infrastructure. Regardless, even with a large increase in the capacity of the state's wood product infrastructure (as was assumed in the low estimates for the increased forest management scenarios), the technical supply of biomass will not be a limiting factor to coupled biochar and carbon credit production in the near term. For example, potential biomass supply is multiple times the feedstock necessary to power 70% of biopower capacity in the West, as outlined in the next section.

However, economical access to biomass from forest restoration is highly variable (Springsteen et al. 2015). The fundamental limitations to forest slash supply appear to be the feedstock price biochar producers are able to pay as well as lack of transparent woody biomass supply chains. In other words, understanding when, where, and how much woody biomass will be generated from forest restoration and at what price. Transparent supply chains must be created in close partnership with large scale land owners, such as the U.S. Forest Service and industrial timber companies. Feedstock price is highly dependent on the type of work being completed and the transportation distance and is another key aspect of transparent and well functioning supply chains. The impact of feedstock price on financial viability of biochar production is examined further in the market scenario analysis. The maximum amount of biochar and corresponding carbon credits that could be generated (Table 1) importantly do not consider economic limitations or viability, but simply characterize the maximum technical potential.

Seven different biochar materials displayed with corn seed for size reference. (Josiah Hunt, Pacific Biochar)

Current potential biomass supply in California is between 1 and 5 million tonnes per year, while future supply could reach as high as 22 million tonnes per year if state goals are achieved. This biomass could be converted to between 250,000 tonnes and 1,300,000 tonnes of biochar currently and up to 5.5 million tonnes if state goals are achieved. The potential for carbon credit production is currently between 500,000 and 3,500,000 and could increase to 15,000,000 yearly with state restoration goals.

Throughout the western United States, roughly 4 and 18 million tonnes of slash are generated per year, while up to 102 million tonnes could be generated in an increased management scenario of roughly four fold - which is in line with many state and federal policies. This translates to a potential biochar production between one and four million tonnes currently and up to 26 million tonnes with a four fold increase in restoration. The potential for carbon credit production is currently between two and 11 million credits and could increase to almost 70 million with state restoration goals.

THE POTENTIAL FOR CARBON CREDIT PRODUCTION IS CURRENTLY BETWEEN 2 AND 11 MILLION CREDITS AND COULD INCREASE TO ALMOST 70 MILLION WITH STATE RESTORATION GOALS.

Biochar-amended compost. (Douglas Gayeton)

At a CA biomass power plant modified for biochar production, a front end loader moves forest biomass to the feed rakes. (Josiah Hunt, Pacific Biochar)

3. Biochar and Carbon Credit Production Capacity

Current biochar production in California is limited to a small number of companies and production is currently below 10,000 tonnes, although accurate numbers are challenging to estimate given the lack of market transparency (Thengane, Kung, Hunt, et al. 2021). Incremental increases in production within the last decade, coupled with the potential for additional income from carbon credits, has attracted both startups as well as investors into the space. Currently, there are two primary methods for biochar production: stand alone biochar production at centralized or mobile units, or coupled biochar and biopower production. We identify the potential for biochar and carbon credit generation in California and throughout the Western U.S. based on surveys of biochar producers (Groot et al. 2018) along with hypothetical industry capacity increases and upgrades to a portion of biopower facilities. In California, there are 26 biopower facilities with a total 551 MW capacity (McIver 2015) and throughout the West there are 42 biopower facilities with a total 893 MW capacity (“U.S. Biomass Power Plants” 2022).

Table 2: Biochar and Carbon Credit Production Potential from Forest Biomass

	Tonnes Feedstock Necessary	Potential Biochar Production	Potential Credit Generation (Low Estimate)	Potential Credit Generation (High Estimate)
California				
Current Stand Alone Production	23,000	6,000	10,000	14,000
50% Industry Capacity Increase	36,000	9,000	15,000	21,000
100% Industry Capacity Increase	48,000	12,000	20,000	28,000
Biopower Light Upgrade	2,200,000	42,000	102,000	114,000
Biopower Heavy Upgrade	2,500,000	212,000	509,000	572,000
Western U.S.				
Current Stand Alone Production	67,000	17,000	32,000	43,000
50% Industry Capacity Increase	102,000	25,500	48,000	64,500
100% Industry Capacity Increase	136,000	34,000	64,000	86,000
Biopower Light Upgrade	3,600,000	69,000	165,000	185,000
Biopower Heavy Upgrade	4,100,000	343,000	824,000	927,000

Stand alone biochar production capacity is based on the market survey results (Groot et al. 2018) which included 46 biochar producers throughout the U.S. and 17 in the Western U.S. specifically. The stand alone industry capacity increases of 50% and 100% assume a proportional increase in industry capacity based on market survey results (Groot et al. 2018). In our biopower light and biopower heavy upgrade scenarios, we incorporate modifications to 70% of biopower capacity, which is believed to be the rough proportion of facilities which are well suited to an upgrade (Hunt, Personal Communication 2021). We further assumed that 2% of feedstock total mass would be captured as biochar in the light upgrade scenario and that 10% would be captured in the heavy upgrade scenario (Friedenthal 2022; Hunt Personal Communication 2021; Hunt and Miles 2020). The potential carbon credit generation incorporates a range of carbon benefit estimations from the IPCC (2019), Carbonfuture (H.P. Schmidt, Kammann, and Hagemann 2021), and Puro (Schimmelpfennig and Glaser 2022) ranging between 1.9 and 2.7 tonnes of CO2 per tonne of biochar produced.

Historically, market challenges such as the lack of demand and high production costs, were noted as limiting biochar production (Thengane, Kung, Hunt, et al. 2021). Niche demand in horticultural applications, biofiltration, and high value agricultural crops has driven demand to date, but the scale of that demand has inhibited industry scale. Other challenges to scale have been noted, such as access to capital, customer perception, lack of market research or promotion, and inconsistent demand. These challenges have limited the biochar market to roughly $100 million per year, although that number is projected to increase in coming years at a compounding rate of 17% ("U.S. Biochar Market Size & Share Report" 2021) which is in line with our modeled 100% industry capacity increase (Table 2) in roughly five years. Linking biochar production with non-merchantable biomass generated during forest restoration will require overcoming these challenges while also creating transparent feedstock supply chains.

Given that most of the potential application in the state is in commercial agriculture, commercial landscaping, home gardening or horticulture, and soil remediation, demonstrating impact in these sectors is key. In general, soil based applications will likely be the biggest market for biochar, especially in high value cropping systems given current prices for biochar (see Section 5).

Biochar production costs are currently between $200 and $1000 per ton, averaging around $400 for the majority of producers (Li et al. 2017; Sahoo et al. 2019), although these numbers are highly variable and are quickly dropping. Average market prices in California vary between $600 and $1300 per tonne of biochar for small quantities (Young and Lawrence 2019) and have decreased significantly from over $2500 per tonne in 2013 (International Biochar Initiative 2015). Current bulk quantity prices are near $200 or lower per tonne, and large-scale market demand would likely support wholesale prices in the range of $80 to $150 per tonne (Hunt, Personal Communication 2021).

Given the increased attention on biochar as a climate solution and the potential for the industry to rapidly scale given the new carbon credit income stream, a new set of challenges arise. Most notable is the need to ensure market demand, or at the very least a viable end use, for biochar. Soil applications in agriculture have been shown to have positive impacts on crop yield (Ye et al. 2020; H. Schmidt et al. 2021) but nevertheless, farmer adoption has been low. Adoption rates may increase as biochar is increasingly viewed as a durable climate change mitigation strategy and carbon credits lower the price of biochar. Another critical challenge to scaling the biochar industry in conjunction with the forest restoration needs throughout the Western U.S. is understanding feedstock supply chains. Given current processes for permitting, planning, and completing forest restoration work, understanding the timing, quantity, and location of forest biomass generated is extremely difficult. Overcoming these challenges will require working with early adopters who are willing to demonstrate the agricultural yield benefits of biochar as a soil amendment, as well as with public and private landowners to better predict the generation of forest biomass from forest restoration projects and provide greater supply consistency.

OVERCOMING THESE CHALLENGES WILL REQUIRE WORKING WITH EARLY ADOPTERS WHO ARE WILLING TO DEMONSTRATE THE AGRICULTURAL YIELD BENEFITS OF BIOCHAR AS A SOIL AMENDMENT, AS WELL AS WITH PUBLIC AND PRIVATE LANDOWNERS TO BETTER PREDICT THE GENERATION OF FOREST BIOMASS FROM FOREST RESTORATION PROJECTS AND PROVIDE GREATER SUPPLY CONSISTENCY.

At a CA biomass power plant modified for biochar production, a trailer is loaded with biochar that has been moistened for dust control and safety. (Josiah Hunt, Pacific Biochar)

4. Carbon Credit Demand Potential

In order to identify potential demand for voluntary carbon credits produced alongside biochar, we spoke with a range of carbon market experts (consultants, project developers, and offset brokers) representing five different organizations to understand how they perceive demand. Biochar credits are generally characterized as being high quality - each credit has considerable co-benefits, there is a high level of certainty in the carbon benefits, and the carbon benefits have medium durability, roughly between 70 and 90% remaining carbon over 100 years. To date, it appears that biochar credits have had effective environmental safeguards to ensure that biochar production does not have unintended negative environmental consequences. Ensuring that biochar production continues to use ecologically sound feedstocks, production processes with minimal emissions and other environmental impacts, and end uses with demonstrable benefits will be critical to the scale and longevity of the industry. In general, the market is increasingly demanding credits with clearly demonstrable durability over longer time frames, credits that are associated with social and environmental co-benefits, and those with high certainty regarding carbon benefits. Although price is still a critical factor in voluntary carbon credit purchasing decisions, this increasing attention on the need for high quality carbon offsets have begun to help bolster the biochar industry.

BIOCHAR CREDITS ARE IN VERY HIGH DEMAND, COMMANDING PRICES BETWEEN $90 AND $600 PER TONNE, WITH MOST PURCHASES BETWEEN $95 AND $125

Biochar's categorization as a carbon dioxide removal credit, as opposed to an emission reduction, also attracts a certain level of attention in line with the recent trend in the market. Biochar credits are in very high demand, commanding prices between $90 and $600 per tonne, with most purchases between $95 and $125 ("Nasdaq Carbon Removal Marketplace and Technologies" 2022), and are purchased essentially the moment they reach the market. Buyers who require a secondary due diligence before purchasing carbon offsets - in other words, buyers who hire consultants to authenticate the veracity of the carbon benefits claims of the offsets they are purchasing - view biochar as a stepping stone between the current carbon offsets on the market and project types such as direct air capture which have the highest level of certainty about the amount of carbon removed. One consultant who specializes in guiding clients towards the highest impact voluntary carbon credits, generally focusing on less than 10% of the total carbon market, sees the demand for $100 biochar generated carbon credits in the tens of thousands annually in the near term. Nasdaq has begun tracking not simply carbon credit pricing, but specifically carbon dioxide removal (CDR) pricing due to the manner in which the market differentiates biochar and other CDR credits.

Despite the high demand amongst a small fraction of quality-conscious buyers, the majority of voluntary carbon offset purchasers are first and foremost still focused on the price of carbon credits, utilizing a portfolio approach to both bring down total costs and spread investment over a range of carbon projects. Given that most offset purchasers are simply looking for the approval of a certified registry to feel comfortable purchasing credits, if biochar credits start to scale to transactions in the hundreds of thousands of tonnes, prices near $100 may not be sustainable despite the perceived quality of such credits. One broker, who has not transacted any biochar credits given the niche market characteristics and lack of substantial supply on the market, said that biochar prices at scale would need to drop below $25 to $30 per ton, in the range of soil carbon and mangrove offsets, for anything but niche purchases under 1,000 tonnes to take place. For most buyers, price is still the most important factor in purchasing decisions and although many anticipate broader carbon market prices to increase, it is challenging to know over what time period and to what extent prices will increase.

5. Biochar Agricultural Application Financial Impact Analysis

Coupled with the need to understand the market demand for carbon credits from biochar production is the need to understand potential options for biochar application and the financial impact of its application. Although biochar application is important to help offset the cost of production in addition to carbon credits to provide revenue to biochar producers, a carbon credit can also only be issued once biochar is safely sequestered in the soil in all the biochar carbon accounting methodologies currently in use, which relies on an end user applying the biochar. End use markets which are able to purchase and use biochar profitably are key in modeling biochar markets.

To better understand viable prices for large volume biochar sales, we analyze the profitability of biochar applications in a few select crops with enough acreage to utilize meaningful quantities of biochar. In this analysis, we assume that if a biochar purchase can produce returns within several harvests, it may have a viable path to market adoption. To determine the near term and long term value of biochar to farmers, we use the Net Present Value (NPV) to estimate the financial impact of biochar application. NPV essentially measures the total growth of an investment. A 20 year time frame is used to harmonize with the assumptions for biochar production financial viability (see Section 6). We couple this economic analysis with a top end estimate of the total addressable market, based on the acreage in production of each crop in California. If this analysis were to be scaled to other crops or larger geographies, these market estimates would grow significantly.

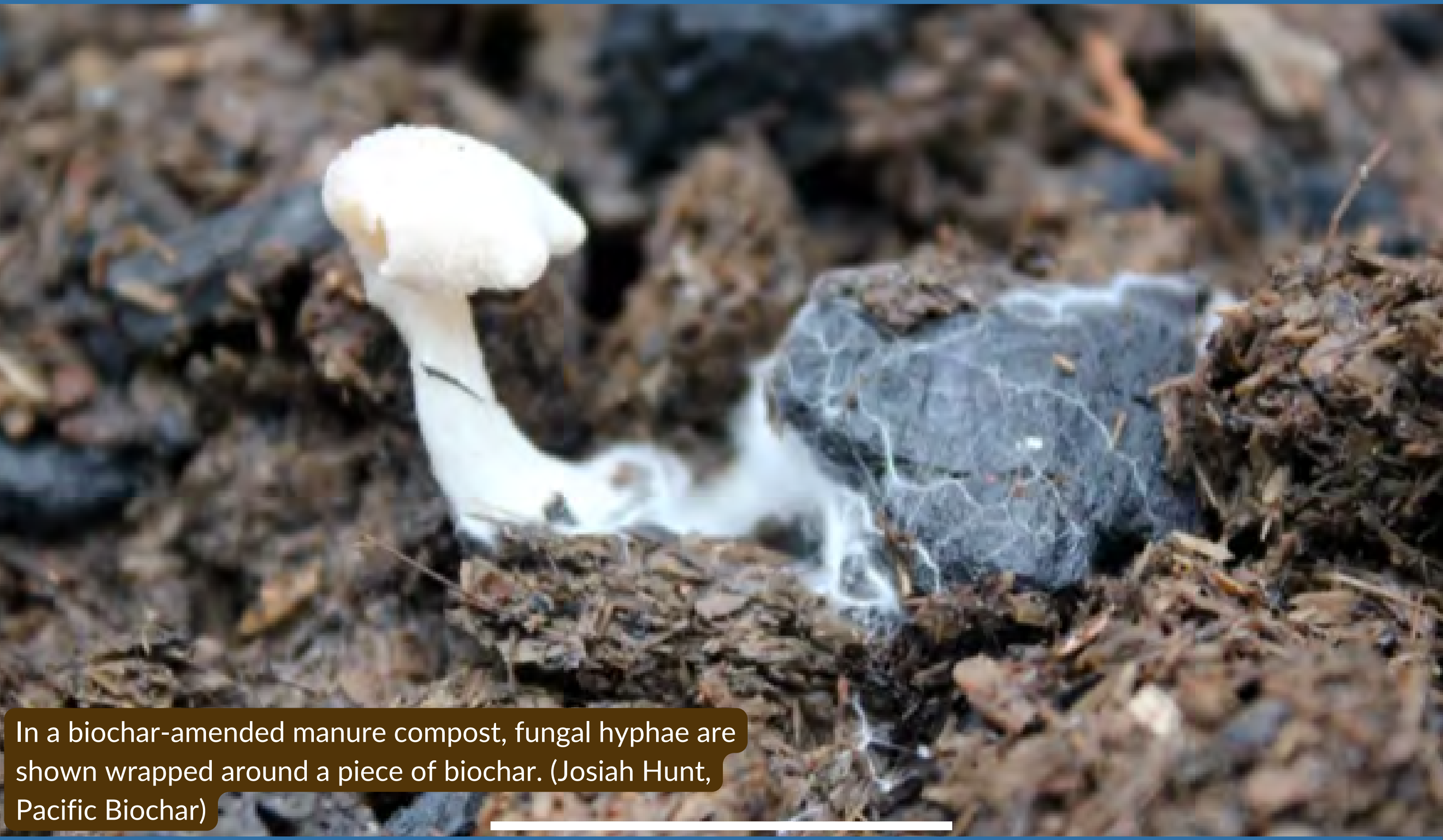
In our assumed market scenario (see Table 3) biochar applications in pistachio orchards have the greatest financial impact, with a yearly additional value of $239 per tonne biochar applied and a return on investment (a positive NPV) after the second year harvest. Biochar applications have a similar impact on wine grapes and almonds, with a $163 and $125 annual impact per tonne of biochar applied and a return on investment in two years. The impact on walnuts is still very high, with a $88 annual impact per tonne and a two year return on investment, but the impact is less substantial than pistachios, wine grapes, and almonds. The lowest impact is on wheat, with a per tonne impact of only $12. Each of these crops represents an enormous potential market, between 4 and 15 million tonnes for each crop and collectively a market over 30 million tonnes with applications every five years.

Table 3: Biochar Crop Yield Assumptions and Economic Impacts in California

Crop		Pistachios	Wine Grapes	Almonds	Walnuts
Harvest per Acre, Tonnes (No Biochar Application)		1.30	6.50	1.00	2.50
Price per Tonne Harvested		$7,500	$1,000	$5,000	$1,400
Additional Crop Value per Year per Acre with Biochar Application		$1,432	$975	$750	$525
Yearly Additional Value per Tonne Biochar		$143	$98	$75	$53
Harvests until Positive NPV	$240 Total Costs per Tonne Biochar	1	3	4	6
20 Year Net Present Value per Acre	$240 Total Costs per Tonne Biochar	$15,555	$9,865	$7,061	$4,257
20 Year Net Present Value per Tonne Biochar	$240 Total Costs per Tonne Biochar	$1,556	$987	$706	$426
20 Year Net Present Value per Acre	$0 Total Costs per Tonne Biochar	$17,841	$12,151	$9,347	$6,543
20 Year Net Present Value per Tonne Biochar	$0 Total Costs per Tonne Biochar	$1,784	$1,215	$935	$654
California Market Size (Million Tonnes Biochar)		5	5	12	4

Our economic impact analysis assumes that four tonnes of biochar are applied per acre (Ye et al. 2020; H. Schmidt et al. 2021) with applications in the first year and every five years following. Although there is literature which highlights the persistence of carbon after applications of biochar (Guo 2015; Glaser and Birk 2012; Knicker 2011; Downie et al. 2011), the authors assume that reapplication is needed to maintain yield increases. There are two biochar cost scenarios modeled, the first assumes a biochar price of $150 per tonne, a shipping cost of $80 per tonne, and a spreading cost of $10 per tonne for a total delivered and spread cost of $240 per tonne biochar or $960 per acre. Shipping costs are based on roughly 6.75 hours roundtrip drive time, costs at $150 per truck hour, and 21 tonnes capacity per truck. The biochar price of $150 per tonne is chosen to harmonize the cost per tonne of biochar to farmers with the price of biochar at which many biochar production scenarios were financially viable (see Section 6).

The second cost scenario assumes a delivered and spread cost of $0 per tonne biochar, to explore the potential economic benefits to farmers if a market support such as a subsidy were used to increase adoption rate. We further assume 10% yield increases given the four tonne per acre application rate, based on findings from two recent meta-analyses (Ye et al. 2020; H. Schmidt et al. 2021). The assumed per acre harvest numbers are based on market averages and prices are based on recent price reports ("No Salty Feelings for the U.S. Pistachio Outlook - West Coast Nut" 2021; "California Grape Acreage Report, 2020 Summary" 2021; "2021 California Almond Objective Measurement Report" 2021; "Walnut/ Raisin/ Prune Report State Summary - 2020 Crop Year" 2021; "Crop Profile for Wheat in California" 2022); ("U.S. Pistachio Prices" 2022; "California Grape Acreage Report, 2020 Summary" 2021; "U.S. Almond Prices" 2022; "Sample Costs to Establish a Walnut Orchard" 2012; "Average Prices for U.S. Wheat from 2014 to 2025" 2022).



In a biochar-amended manure compost, fungal hyphae are shown wrapped around a piece of biochar. (Josiah Hunt, Pacific Biochar)

An experimental biologically activated biochar-fertilizer product, with a subtle white coating of soil microorganisms. (Josiah Hunt, Pacific Biochar)

MARKET ANALYSIS IMPLICATIONS: FARMER ADOPTION OF BIOCHAR AS A SOIL ADDITIVE

Our production analysis shows that biochar can have a highly positive effect on certain crops, particularly high value crops such as nuts and wine grapes. The modeling also suggests that lower value crops, such as wheat, may not present a viable biochar market when delivered and applied biochar prices are $240. However, lower value crops still may benefit from biochar applications, leaving open the possibility of using subsidies or other policy mechanisms to encourage biochar applications given the high carbon benefits and other co-benefits.

BIOCHAR CAN HAVE A HIGHLY POSITIVE EFFECT ON CERTAIN CROPS, PARTICULARLY HIGH VALUE CROPS SUCH AS NUTS AND WINE GRAPES.

The technical market potential for biochar as an agricultural soil amendment is enormous. However, our estimates and others do not take into consideration the rate of farmer adoption, only the number of potential acres and an assumed application rate of four tonnes of biochar per acre. Using compost addition as a precedent, agricultural practices that are profitable and cost saving practices can sometimes take decades to be adopted at significant levels. Assuming high volumes of biochar production driven by support from high carbon prices, biochar supply might increase at a faster pace than farmer demand to purchase biochar. Solutions to address this hypothetical problem might include 1) embedding the cost of biochar application to farmland into the price of each carbon credit, with the potential to claim the resulting co-benefits in the carbon credit, 2) subsidizing biochar applications through government programs such as California's Department of Food and Agriculture's Healthy Soils Initiative or the U.S. Department of Agriculture's Environmental Quality Incentives Program (EQIP), or 3) creating financial tools for loans which embed anticipated future crop yields or other monetizable benefits into expected future income, as has been used for residential energy efficiency financing.

6. Biochar Production Investment Potential and Market Scenario Analyses

To estimate the financial viability of coupled biochar and carbon credit production in various market scenarios, we model four different production systems based on existing techno-economic analyses in the academic literature: mobile biochar produced via a small scale transportable system in forests (Thengane, Kung, York, et al. 2021), centralized biochar produced in a dedicated industrial facility (Friedenthal 2021), a 25 MW biopower plant with a light upgrade which harvest partially combusted biomass as biochar (Wiltsee 2000; Hunt and Miles 2020), and a 25 MW biopower plant with a heavy upgrade which incorporates three kilns to produce biochar alongside syngas, which is combusted to generate electricity (Friedenthal 2021). Throughout this report, any reference to production systems are the technologies from these references and all economic assumptions are based on these production systems.

Internal Rate of Return (IRR) is a metric used to measure annual profitability of an investment and was the primary metric used in our analysis. Net Present Value (NPV) was used as a secondary metric and is essentially the magnitude of the return on a potential investment.

In our assumed market scenario (see Table 4) biopower with a light upgrade on a 25 MW facility has an IRR of 29% with a twenty year NPV of $10.5 million. Biopower with a heavy upgrade on a 25 MW facility has an IRR of 9% and has a NPV of $5.9 million. Mobile biochar has an IRR of 2% and NPV of $-0.15 million. Centralized biochar has an IRR of -1% and a NPV of $-8.7 million. In order to be conservative, a contingency was added to the capital expenditures (CAPEX) costs for the light and heavy upgrades of 50% and 30% respectively given the existing amount of contingency already built into these estimates.

This analysis is limited in its focus on five primary variables: operational expenditures, capital expenditures, feedstock costs, biochar price, and carbon credit prices. Some of the production systems modeled here represent a potential for investment from traditional investors while others may be less directly investible. However, given the high potential for societal benefits from biochar, production systems which have a lower return on investment may still represent valuable projects for private, state, or federal sponsorship. This analysis does not attempt to identify the best biochar production system - that will vary considerably depending on a range of factors - but simply to investigate the financial viability of four potential production systems.

Table 4: Assumed Market Scenario

Feedstock cost	$	50	Per tonne
Biochar Price	$	200	Per tonne
Carbon Price	$	80	Per tonne CO2
Carbon Benefit		2.5	tCO2 per tonne biochar
Capital Expenditures			
Biopower (25MW) Light Upgrade	$	4,000,000	
Biopower (25MW) Heavy Upgrade	$	15,000,000	
Biochar Mobile	$	750,000	
Biochar Centralized	$	20,000,000	
Operational Expenditures (not including feedstock costs)			
Biopower (25MW) Light Upgrade	$	10	Per tonne biochar*
Biopower (25MW) Heavy Upgrade	$	22	Per tonne biochar**
Biochar Mobile	$	225	Per tonne biochar
Biochar Centralized	$	33	Per tonne biochar
	*Assumes 1/2 FTE needed for light upgrade		
	**Assumes 3 FTE needed for heavy upgrade		
Biochar Production			
Biopower (25MW) Light Upgrade		6,160	Tonnes/ year
Biopower (25MW) Heavy Upgrade		18,144	Tonnes/ year
Biochar Mobile		1,350	Tonnes/ year
Biochar Centralized		18,144	Tonnes/ year
Net Present Value			
Biopower (25MW) Light Upgrade	$	10.50	Million/ 20 years
Biopower (25MW) Heavy Upgrade	$	5.94	Million/ 20 years
Biochar Mobile	$	(0.15)	Million/ 20 years
Biochar Centralized	$	(8.70)	Million/ 20 years
Internal Rate of Return			
Biopower (25MW) Light Upgrade		29%	
Biopower (25MW) Heavy Upgrade		9%	
Biochar Mobile		2%	
Biochar Centralized		-1%	


A trailer of biochar unloaded at Compost Solutions Inc in Orland CA. (Josiah Hunt, Pacific Biochar)

MARKET ANALYSIS I: BIOCHAR AND CARBON MARKET PRICE EFFECT ON INTERNAL RATE OF RETURN

To understand how biochar and carbon prices affect profitability, we model the Internal Rate of Return (IRR) of each production system with assumed biochar prices between $100 and $250 per tonne and assumed carbon prices between $0 and $100 per tonne CO2. Biopower with light upgrades on a 25 MW facility has an IRR between -7% and 40%, biopower with heavy upgrades on a 25 MW facility has an IRR between -15% and 19%, biochar mobile has an IRR between -16% and 18%, and biochar centralized had an IRR between -2% and 9%. Feedstock costs were held constant at $50 per tonne.

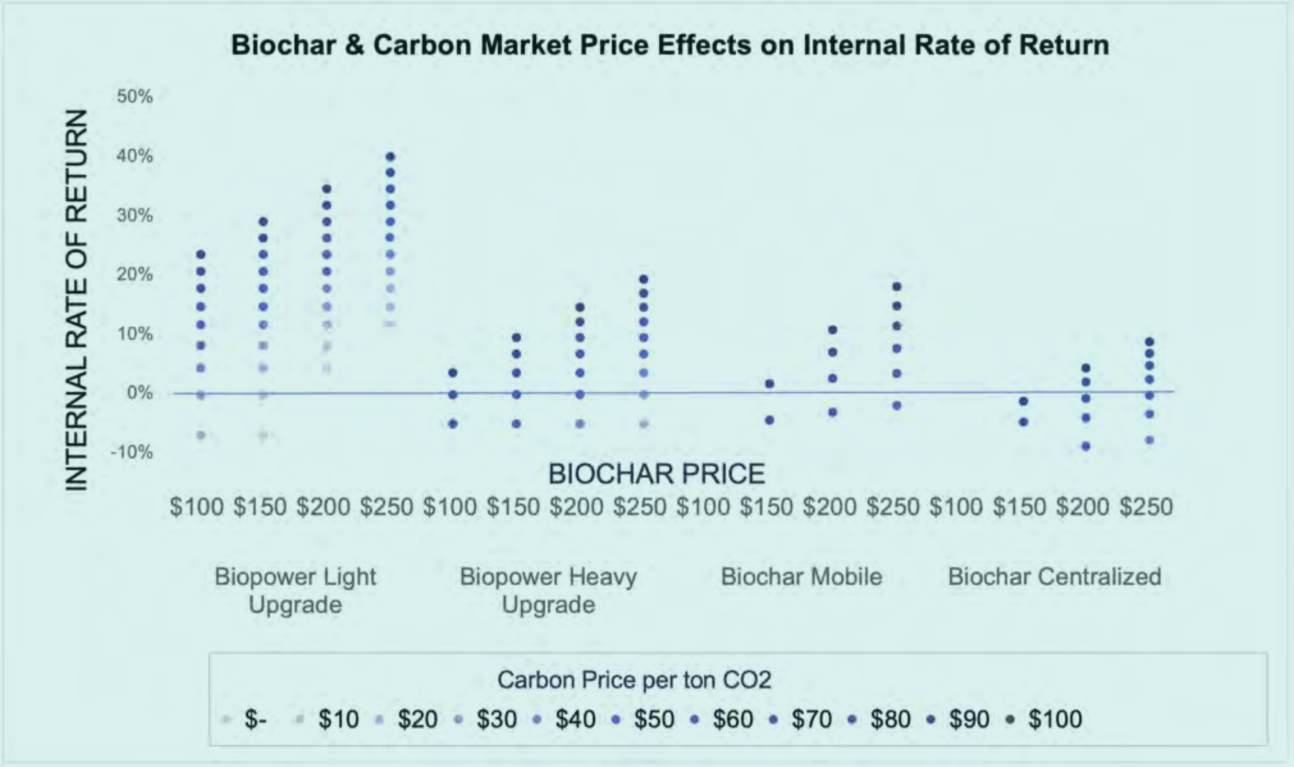


Figure 1: Depiction of the absolute internal rate of return (IRR) of four biochar production types with biochar prices between $100 and 250 and carbon prices between $0 and 100 per tonne CO2. Feedstock costs are fixed at $50 per bone dry tonne. IRR values below negative 10% are excluded.

Assuming inflexible biochar price and flexible carbon price, we capture the modeled breakeven carbon price (in this case the landed carbon price to the producer, including transportation, fees, etc) for each production system given IRRs of 5%, 10%, and 15% in table 5. The breakeven carbon price essentially determines the price at which carbon credits would need to be sold in order to achieve a predetermined IRR, holding feedstock costs at $50 per tonne and biochar price at four different points in turn ($100, $150, $200, $250). Depending on the assumed price of biochar, the breakeven carbon price for biopower with light upgrade is between $0 and $70 per tonne CO2, between $45 and $140 per tonne CO2 for biopower with a heavy upgrade, between $65 and $155 per tonne CO2 for mobile biochar, and between $80 and $200 per tonne CO2 for centralized biochar. These numbers also assume that the carbon price is the final price realized by the producer after accounting for all transaction costs, commissions, etc.

Table 5: The breakeven carbon credit price which provides Internal Rates of Return (IRR) of 5%, 10%, and 15% with biochar prices between $100 and $250 per tonne. Feedstock costs are fixed at $50 per tonne.

	Biochar Price	IRR 5%	IRR 10%	IRR 15%
Biopower Light Upgrade	$100	45	60	70
	$150	20	35	50
	$200	0	15	30
	$250	0	0	10
Biopower Heavy Upgrade	$100	105	120	140
	$150	85	105	120
	$200	65	85	100
	$250	45	65	85
Mobile Biochar	$100	130	140	155
	$150	105	120	135
	$200	85	100	115
	$250	65	75	90
Centralized Biochar	$100	145	175	200
	$150	125	150	180
	$200	105	130	160
	$250	80	105	135

MARKET ANALYSIS II: BIOCHAR AND FEEDSTOCK COST EFFECT ON INTERNAL RATE OF RETURN

To understand how biochar and carbon prices affect profitability, we model the Internal Rate of Return (IRR) of each production system with biochar prices between $100 and $250 with feedstock costs between $0 and $120 per ton. Biopower with light upgrades has an IRR between -23% and 47%, biopower with heavy upgrades has an IRR between -5% and 36%, biochar mobile has an IRR between -9% and 26%, and a biochar centralized facility has an IRR between -15% and 25%. The carbon price was held constant at $80 per ton.

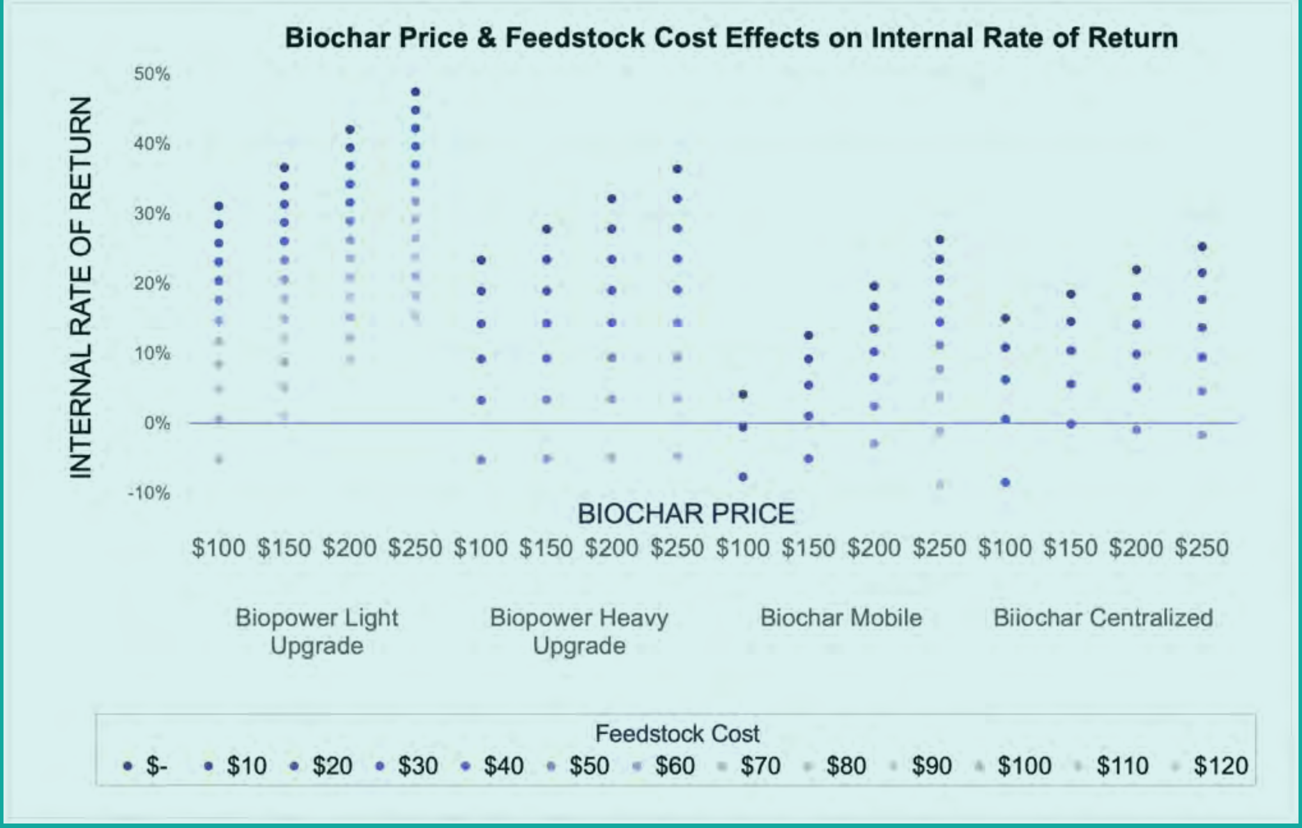


Figure 2: Depiction of the absolute internal rate of return (IRR) of four biochar production types with biochar prices between $100 and 250 and feedstock costs between $0 and 120 per bone dry ton. Carbon price is fixed at $80 per ton. IRR values below negative 10% are excluded.

We capture the breakeven feedstock costs for each production system dependent on the IRR needed by investors given IRRs of 5%, 10%, and 15% in table 5. Depending on the assumed price of biochar, the breakeven cost per tonne of feedstock for biopower with light upgrades is between $60 and $150, between $20 and $70 per tonne for biopower with heavy upgrades, between $-30 and $70 per tonne for mobile biochar production, and between $0 and $50 per tonne for centralized biochar production. Negative values show situations in which a production system would need to be paid to take feedstock. In each scenario, these numbers assume the carbon credit price is fixed at $80 per tonne.

Figure 6: The breakeven feedstock cost which provides Internal Rates of Return (IRR) of 5%, 10%, and 15% with biochar prices between $100 and $250 per tonne. Feedstock costs are fixed at $50 per tonne.

	Biochar Price	IRR 5%	IRR 10%	IRR 15%
Biopower Light Upgrade	$100	90	75	60
	$150	110	95	80
	$200	130	115	100
	$250	150	135	120
Biopower Heavy Upgrade	$100	40	30	20
	$150	50	40	30
	$200	60	50	40
	$250	70	60	50
Mobile Biochar	$100	0	-15	-30
	$150	20	10	0
	$200	45	30	15
	$250	70	50	35
Centralized Biochar	$100	20	10	0
	$150	30	20	10
	$200	40	30	20
	$250	50	40	30

SENSITIVITY ANALYSIS

A sensitivity analysis demonstrates how fluctuations in specific variables affect the baseline IRR. Each fluctuation is expressed as an absolute increase in IRR. Both biopower with light upgrades and heavy upgrades are most sensitive to changes in capital expenditures, with a 40% decrease in cost leading to IRR increases of 20% and 9%, respectively. Both biopower with light upgrades and heavy upgrades are least sensitive to changes in operational expenditures, with a 40% decrease in cost leading to IRR increases of 0% and 1%, respectively. Biochar mobile is most sensitive to changes in operational expenditures with a 40% increase in cost leading to an IRR decrease of 15%. Biochar mobile is least affected by variations in capital expenditures, with a 40% decrease leading to an IRR increase of 5%. Biochar centralized is most sensitive to changes in feedstock price, with a 40% decrease in cost leading to an IRR increase of 11%. Biochar centralized is least sensitive to changes in operational expenditure with a 40% decrease leading to an IRR increase of 2%.

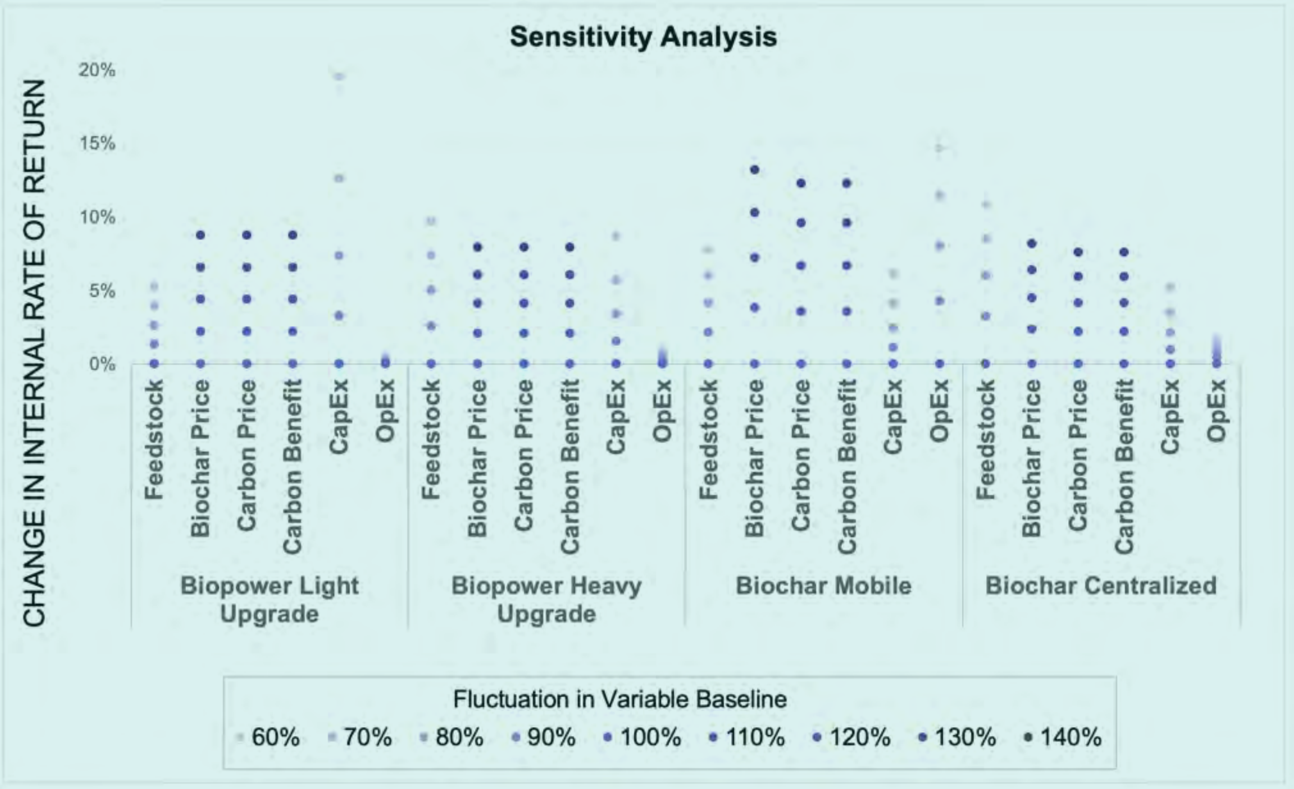


Figure 3: Depiction of the absolute change of the internal rate of return from the baseline scenario with a stepwise change in the independent variables for each of the four technologies. Negative values are excluded.

INVESTMENT POTENTIAL IMPLICATIONS: CONNECTING BIOCHAR, CARBON CREDITS, AND FEEDSTOCK COSTS

Our market analyses show that each production system can be profitable in certain market conditions. Given the constraints of this analysis, particularly in limiting carbon price to $100 per tonne CO_2, each production system simultaneously needs income from the biochar produced as well as carbon credits to achieve profitability. The only exception is biopower with a light upgrade, which may be profitable with either high carbon prices (over roughly $100 per tonne) or very high biochar prices (over roughly $250 per tonne) alone.

EACH PRODUCTION SYSTEM CAN BE PROFITABLE IN CERTAIN MARKET CONDITIONS.

Feedstock costs are a critical variable affecting profitability. Our assumed market scenario holds feedstock costs at $50 per tonne, which is an accurate representation of the typical current costs to remove biomass from the forest and transport it to a centralized location for processing. In certain instances, that price may be much higher or lower than this assumed cost.

However, mobile biochar may be able to operate directly at a forest restoration site, effectively reducing the cost of feedstock close to $0 per tonne. In a situation in which feedstock costs are close to $0, mobile biochar is profitable with biochar prices at $100 per tonne and carbon prices at $80 per tonne, given the production system modeled here (Thengane, Kung, York, et al. 2021) (see Figure 2). This may provide a viable option in many cases for forest managers, such as the U.S. Forest Service, to defray some of the costs of dealing with the biomass from forest restoration projects, particularly if that biochar is applied directly to the forest. For instance, pile and burning costs for unmerchantable biomass on U.S. Forest Service land can be $300-600 per acre (Foster Personal Communication, 2022). Assuming 2 tonnes of biochar generated from an equivalent amount of unmerchantable timber, the Forest Service could subsidize biochar production up to $150 and 300 per tonne biochar ($300 and 600 per acre) and potentially reduce costs compared to pile burning.

Given the variety of situations this analysis aims to capture, it is important to analyze potential investments on a case by case basis by examining feedstock costs, which are highly dependent on transportation, in addition to income from biochar and carbon offsets, as well as necessary return on investment.

7. Level of Investment Needed

There is potential for both private and public investment in this space, either from landowners, or from outside investors interested in the growing biochar and carbon markets. Alongside traditional investments is the potential for cost savings for large scale landowners engaging in forest management. In certain instances, such as with light and heavy upgrades, there is a more compelling argument for outside investments given the potential for returns on investment. Centralized and mobile biochar systems may not be as attractive to private investors, but can still play an important role in reducing the costs associated with large scale forest restoration and can be an attractive option for land owners and managers. In either situation, it is important to acknowledge the limitations of a modeling exercise such as this - we are inherently limited by the information available to the public. Biochar production processes and investment potential are evolving rapidly and should be examined on a case by case basis.

While only accounting for the biomass generated from forest thinning and not the potential from agricultural, municipal, and other sources, the potential for investment is large. With relatively short timelines between an initial investment and production, investments in light and heavy upgrades as well as mobile biochar can produce biochar and offsets within a year or two of securing funding. Centralized production may require more time to operationalize, but can still be producing biochar and carbon credits in less than five years. Table 7 shows that with a 10 million dollar investment, up to approximately 181,000 tonnes of biochar and over 400,000 carbon credits could be generated over 10 years. With a 100 million dollar investment, almost two million tonnes of biochar and over four million carbon credits could be generated over 10 years.

WITH A 100 MILLION DOLLAR INVESTMENT, ALMOST TWO MILLION TONNES OF BIOCHAR AND OVER FOUR MILLION CARBON CREDITS COULD BE GENERATED OVER 10 YEARS.

Table 7: Coupled Biochar and Carbon Credit Production Potential 10 and 100 Million in Investments

	10 Million					
Years	1		5		10	
	Biochar	Credits	Biochar	Credits	Biochar	Credits
Light Upgrade	15,000	37,500	77,000	192,500	154,000	385,000
Heavy Upgrade	7,000	17,500	33,000	82,500	66,000	165,000
Mobile Production	18,000	41,400	91,000	209,300	181,000	416,300
Centralized production	-	-	58,000	133,400	115,000	264,500

	100 Million					
Years	1		5		10	
	Biochar	Credits	Biochar	Credits	Biochar	Credits
Light Upgrade	154,000	385,000	770,000	1,925,000	1,540,000	3,850,000
Heavy Upgrade	66,000	165,000	329,000	822,500	657,000	1,642,500
Mobile Production	181,000	416,300	907,000	2,086,100	1,813,000	4,169,900
Centralized production	-	-	576,000	1,324,800	1,152,000	2,649,600

While $10 and $100 million investments can enable large scale biochar and carbon credit production, the total investment potential in biochar production is much higher. Accounting for only forest biomass as a feedstock and no other feedstock sources such as agriculture, municipal or other, up to 50 billion dollars could be invested in biochar production (see Table 8).

UP TO 50 BILLION DOLLARS COULD BE INVESTED IN BIOCHAR PRODUCTION.

Table 8: Total Investment Needed to Utilize All Forest Biomass from Western U.S.

Technology	Billions
Light Upgrade	$40
Heavy Upgrade	$20
Mobile Production	$50
Centralized production	$30

We predict that the two main limitations to scaling investments to this level are 1) an assured end use for biochar, either as an agricultural soil amendment or other beneficial use, as well as 2) a transparent and consistent feedstock supply chain. Working with potential customers, such as large scale agricultural producers and early adopters, to provide a more nuanced answer to the yield impact that biochar has on agricultural land may help stimulate market demand. Creating transparent supply chains is largely dependent on tracking forest restoration project development to better understand the timing, quantity, and location of non-merchantable forest biomass generation.

THE TWO MAIN LIMITATIONS TO SCALING INVESTMENTS TO THIS LEVEL ARE 1) AN ASSURED END USE FOR BIOCHAR, EITHER AS AN AGRICULTURAL SOIL AMENDMENT OR OTHER BENEFICIAL USE, AS WELL AS 2) A TRANSPARENT AND CONSISTENT FEEDSTOCK SUPPLY CHAIN.

8. Conclusions and Implications

Throughout the Western U.S. there is considerable potential to link biochar production with forest restoration while providing a value-added use for currently non-merchantable woody biomass. Today in the West, there are between roughly 5 and 20 million tonnes of non merchantable biomass generated yearly during restoration projects, most of which is pile burned or left to decompose in the forest. Those estimates increase to 25 and 100 million tonnes of biomass yearly if much needed restoration goals are achieved. Making biochar from this biomass can provide both a product with many beneficial potential end use cases - such as agricultural soil additions, bio-filtration, forestry applications, and many others - and high quality carbon offsets. Using the non-merchantable woody biomass throughout the Western U.S. could provide up to 25 million tonnes of biochar and 70 million high quality carbon offsets each year.

Currently, stand-alone biochar production is limited to a few thousand tonnes per year in the West, but there is potential to build both dedicated biochar facilities as well as upgrade existing biopower facilities to coproduce biochar and carbon credits at scale. The carbon market is increasingly demanding carbon credits from biochar production, with prices commonly between \$95 and \$125 per tonne CO_2 and reaching as high as \$600. These prices are well aligned with the U.S. Department of Energy's Carbon Negative Shot, with a goal of removing CO_2 from the atmosphere and durably storing it for less than \$100 per tonne (U.S. Department of Energy n.d.). If biochar-generated carbon credits are produced in the magnitude examined in this report, carbon credit prices will likely fall. However, today's market can easily absorb tens of thousands of carbon credits at current prices. While in certain cases high carbon prices can single-handedly pay for the production of biochar, developing viable end use markets for biochar will be critical to the development of the biochar industry. Our analysis shows that certain crops can benefit economically from biochar application, with some crops receiving a net financial return during the second harvest after application.

This report finds that biochar production is profitable in many scenarios, with light upgrades to 25 MW biopower facilities standing out as the most financially viable from a traditional investment standpoint, with internal rates of return between 10% and 35% in most cases. Dedicated biochar production, while not as seemingly investible as upgrades to biopower facilities, may play a powerful role in defraying costs traditionally associated with pile burning non-merchantable woody biomass. While pile burning costs may be near $300 and $600 per acre, mobile biochar systems may be able to process a comparable amount of biomass and cut costs significantly. Feedstock costs are key to make biochar production profitable in many scenarios, although high carbon or biochar prices can compensate for high feedstock costs in some situations. Given the high variability in financial viability due to costs and potential sales prices, it is important to consider the feasibility of biochar production on a case by case basis and whether the goal of production is return on investment or reducing costs associated with disposing of non-merchantable biomass from forest restoration projects. With that in mind, the total investment potential in this space is between $20 and $50 billion dollars assuming forest restoration goals are met in the coming years. In the near term, investments totaling $100 million would generate up to four million carbon credits in the next 10 years.

Despite the enormous potential of biochar as both a product and generator of carbon offsets, there are several roadblocks to industry scale. From a technical standpoint, the lack of current production infrastructure limits scale. But more fundamentally, uncertain demand for biochar, lack of transparent biomass supply chains, and a lack of historic investment in this space must be overcome. Working with farmers and other land managers to demonstrate the impact of biochar on production on a large scale is necessary to establish sustained demand, while collaboration with the U.S. Forest Service and potentially large private landowners to develop transparent biomass supply chains with clear timing, cost, quantity, and location of biomass generation is critical. Both of these will be key to attracting historically wary investors.

WORKING WITH FARMERS AND OTHER LAND MANAGERS TO DEMONSTRATE THE IMPACT OF BIOCHAR ON PRODUCTION ON A LARGE SCALE IS NECESSARY TO ESTABLISH SUSTAINED DEMAND, WHILE COLLABORATION WITH THE U.S. FOREST SERVICE AND POTENTIALLY LARGE PRIVATE LANDOWNERS TO DEVELOP TRANSPARENT BIOMASS SUPPLY CHAINS WITH CLEAR TIMING, COST, QUANTITY, AND LOCATION OF BIOMASS GENERATION IS CRITICAL.

To continue growing the biochar industry, producers will likely need to follow the example of the producers who have already begun to leverage the niche characteristics of the carbon credits they produce to enhance their own growth. Moving forward, there are three potential pathways for the biochar industry to scale and utilize biomass from forest management and fuel thinning projects. Either 1) the carbon market will need to sustain high carbon prices, 2) a subsidy or other mechanism will need to decrease the cost of feedstock biomass, or 3) production will need to take advantage of economies of scale to bring down biochar prices while increasing biochar and carbon credit production, providing conditions necessary for credits to be widely available at prices the market will sustain. Given the growing interest in co-produced biochar and carbon credits, and the need to massively expand the pace and scale of forest restoration through the Western U.S., increased attention, investment, and collaboration is already happening in this space. The combination of these forces could combine to overcome the historical barriers to the development of the biochar industry.

9. Methods

Woody Biomass Supply, Potential Biochar Production, and Potential Carbon Credit Production

Each of the estimates for supply of currently non-merchantable biomass in bone dry tonnes (BDT) is based on the following equations and the scenario specific assumptions. The wood products capacity estimates for California are based directly on industry information (University of Montana 2016; McIver 2015) and conversions from million cubic feet, the unit used in the report, to million bone dry tonnes (MMBDT) was based on conversion factors in Shelley (2007) with one hundred cubic feet of logs equating to 1.2 BDT. The total capacity of the wood products infrastructure is derived from the current merchantable timber harvest and the current percent of the wood products infrastructure utilized (McIver 2015; University of Montana 2016). The capacity estimates for the West assume the capacity is six times as large as California based on the size of the timber harvest statistics in information for Washington, Oregon, Montana, Idaho, and California for the year of 2016 ("University of Montana Bureau of Business and Economic Research" 2013). Potential biochar production is calculated by assuming a 0.25 mass yield from woody biomass to biochar. The potential carbon credit generation incorporates carbon benefit estimations from the IPCC (IPCC 2019), Carbonfuture (H.-P. Schmidt, Kammann, and Hagemann 2021), and Puro (Schimmelpfennig and Glaser 2022) with low estimated of 1.9 tonnes of CO_2 per tonne biochar produced and high estimated of 2.7 tonnes of CO_2 per tonne biochar produced.

$$Current\ Low = \frac{Total\ Merchantable\ timber\ harvest}{\%\ merchantable\ harvest\ per\ acre} * \%\ Non\ Merchantable\ Biomass\ per\ Acre$$

$$Current\ High = Acres\ Treated * Biomass\ Harvested\ per\ Acre - Current\ Industry\ Capacity\ (BDT)$$

$$Increased\ Low = Acres\ Treated * Non\ Merchantable\ Biomass\ per\ Acre$$

$$Increased\ High = Acres\ Treated * Biomass\ Harvested\ per\ Acre - Current\ Industry\ Capacity\ (BDT)$$

Table 9: Biomass Supply Assumptions

Biomass harvested per acre	20	BDT	Rummer et al. 2005
Merchantable Biomass per acre	60	%	Bill Stewart Private Communication 2021
Non-merchantable biomass per acre	40	%	Bill Stewart Private Communication 2021
Total Merchantable Timber Harvest (CA)	2.12	MMBDT	University of Montana 2016
Wood products infrastructure total capacity (CA)	3	MMBDT	University of Montana 2016 and McIver 2015
Wood products infrastructure total capacity (West)	18	MMBDT	*Estimated from University of Montana 2013 statewide harvest data
Current percent wood products infrastructure utilized	71	%	University of Montana 2016 and McIver 2015
California Acres Treated			
Current Low	NA		
Current High	250,000	Acres	
Increased Low	500,000	Acres	
Increased High	1,000,000	Acres	
Western U.S. Acres Treated			
Current Low	1,500,000	Acres	
Current High	1,500,000	Acres	
Increased Low	2,000,000	Acres	
Increased High	4,000,000	Acres	

Biochar Production Capacity Estimates

Stand alone production capacity is based on the market findings from Groot et al. (2018), which surveyed producers in the biochar industry throughout the U.S. Stand alone production estimates are based on biochar production of 45,000 tonnes per year, likely a conservative estimate. 17 of the 46 producers were located in the Western U.S., with 12 producers on the West Coast. We assume that six of the producers are located in California. Production estimates are proportional, based on the number of producers in each region and the total amount of biochar produced yearly. Potential increases in industry capacity are calculated as proportional increases in total capacity based on the estimation of current stand alone production capacity.

Light upgrade production scenario assumes that 70% of the biopower capacity in the state and throughout the West is eligible for a light upgrade based on conversation with practitioners (Hunt 2021), which converts 2% of feedstock into biochar. The biochar output of the light upgrade to biopower is calculated using the equations and assumptions below.

The heavy upgrade production scenario assumed that 70% of all biopower capacity in the state is eligible for a heavy upgrade which coupled the production of biochar with biopower, yielding 10% of the feedstock as biochar.

Table 10: Biochar and Carbon Credit Generation Estimations

Variable	Assumption		Descriptions	Source
	Light Upgrade	*Heavy Upgrade*		
BioCap	551		Total state biopower capacity (megawatts)	McIver 2015
BioElig	70%		Proportion of BioCap eligible for upgrade	Assumption
CapFac	70%		Capacity factor of biopower production	Assumption
ElecGenEff	20%		Electrical energy generation efficiency	Assumption
MassYield (light)	2%	10%	Biomass to biochar generation efficiency	Hunt and Miles 2020
BioHeat	5.58		Heating value (mWh) per tonne biomass	Argonne National Lab 2021
CharHeat	6.11		Heating value (mWh) per tonne biochar	Argonne National Lab 2022
CharConvert	60%		Realizable energy content change	Intermediate output
EffCost	33.96%		Energy content percent change (wet basis 43% to 0%)	Forest Research 2022
TotFeed	2,200,000	2,500,000	Tons of biomass needed to fulfill statewide biopower demand	Intermediate output

Feedstock is the amount of biomass needed to generate the portion of the biopower energy output in the state which is eligible for a light or heavy upgrade.

$$Feedstock = \frac{BioCap*BioElig*CapFac*365*24}{BioHeat * ElecGenEff}$$

Biochar yield is the amount of biochar which could be produced from the feedstock in the above equation. There are different generation capacities for light and heavy upgrades.

$$BiocharYield = Feedstock * MassYield$$

Increased feedstock is the additional amount of feedstock needed to compensate for the biochar generation.

$$AddFeed = \frac{BiocharYield*CharHeat}{CharConvert*BioHeat}$$

$$CharConvert = \frac{Bioheat*(1-EffCost)}{CharHeat}$$

$$TotFeed = AddFeed + Feedstock$$

Carbon Offset Generation

To calculate the carbon offsets generated by standalone biochar producers (not coupled biopower and biochar producers), we use the carbon benefits of 1.9 and 2.6 tCO2 per tonne biochar based on the IPCC quantification methodology (IPCC 2019). Both the high and low scenarios assumed a biochar carbon content of 80% with 65% carbon remaining after 100 years in the low scenario and 89% carbon remaining in the high scenario.

To calculate carbon offsets generated by coupled biopower and biochar producers, we use carbon benefits of 2.4 and 2.7 tonnes CO2 per tonne biochar based on the Puro (high estimate) and Carbonfuture (low estimate) methodologies. The Puro (Schimmelpfennig and Glaser 2022) and Carbonfuture (H.-P. Schmidt, Kammann, and Hagemann 2021) methodologies differ from the IPCC methodology most significantly in that the IPCC methodology does not account for emissions during the creation or transportation of the biochar or feedstock. Puro and Carbon Future differ from each other primarily in how the margin of safety is calculated, which is part of the credit quantification methodology. The benefits for the biochar produced from light and heavy upgrades is estimated using the quantification approaches of Puro and Carbonfuture because the examples from a specific coupled biopower and biochar facility were available at the time of this analysis. In the end, the estimates from the IPCC, Puro, and Carbonfuture are all relatively similar and we chose the numbers that we felt most accurately represented the high and low estimates of credits that could be generated.

Carbon Credit Demand Potential
Quantifying the demand for biochar carbon credits is based on the opinions of six experts representing five organizations, including consultants, project developers, and brokers. Between September and December 2021, these conversations focused on how perceptions of quality in the marketplace influence demand, whether there was increasing demand for credits from removals vs emissions, at what price point various quantities of biochar credits could be sold, and how market drivers have changed over time. These interviews were semi-structured and confidential.

Biochar, Carbon Credit, and Feedstock Market Scenario Analysis
Market analyses are based on deconstructed techno-economic analyses (TEA), which are modeled in Excel to calculate the Net Present Value and Internal Rate of Return for each market scenario. The biomass feedstock needed for a 25 MW biopower plant (Wiltsee 2000) is coupled with light (Hunt and Miles 2020) and heavy (Friedenthal 2022) upgrade scenarios with any changes to those scenarios done in consultation with the authors. Labor costs for the light and heavy upgrades to the 25MW biopower plant are based on full time employee costs of $132,500 (adjusted for 2022 inflation) (The Beck Group 2015). Mobile biochar is based on a mobile system (Thengane, Kung, York, et al. 2021), which is a small-scale system which produces biochar in forest. Centralized biochar is based on Friedenthal (2022) which is a large industrial facility. Carbon benefits used were based on Puro, Carbonfuture, and IPCC estimates. A 2.5 tonne CO_2 benefit per tonne biochar was used for both light and heavy upgrade scenarios, which was a conservative average between from the Puro and Carbonfuture methodologies described above. 2.3 tonnes CO_2 benefit per tonne biochar was used for mobile and centralized biochar, which was using the IPCC methodology assuming that the biochar was 80% carbon and that 80% of the carbon remained after 100 years.

Sensitivity Analysis
The sensitivity analysis is completed by changing each variable in increments of 10% in each direction, examining both a 40% decrease and increase in each variable. Outcomes are recorded and represented based on the absolute change in IRR of each production system.

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