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Sustaining agricultural economies: regional economic impacts of biochar production from waste orchard biomass in California's Central Valley

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Abstract

The prominent role of agriculture in greenhouse gas (GHG) emissions has increased global interest in biochar. This carbonaceous biomass product 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 and 17.69 new full- and part-time jobs per year that would contribute between $1.2 and $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.

Keywords Sustainable agriculture · Underserved communities · Air pollution · Economic analysis · Regional impacts

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1 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 paper 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 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 CO_2 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 a 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 NH_3, CH_4, and N_2O emissions (Akdeniz, 2019; 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 paper 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 USA. Cherubin et al. (2018) rank the USA 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 (Nematian et al., 2021). 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 (Keske, 2020). California ranks among the top agricultural-producing states and generates at least 70 million tons of waste biomass per year (Breunig et al., 2018). According to Kaffka et al. (2013), California also has at least 8000 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. The 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 employment, labor income, total industry output, and total value added. Though California is poised to phase out burning agricultural wastes by 2025, this study documents the positive economic benefits of converting biomass into soil amendment and the potential to form a new economic sector.

1.1 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 and 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 (Li et al., 2018; Nematian et al., 2021).

Some studies in the USA 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 & Yoder, 2010; 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 USA, 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, they 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 and Jolley (2019) determined that the economic contribution of the wood industry in Appalachian Ohio improves investment and value-added opportunities that support economic growth.

2 Materials and methods

2.1 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. Following (Joshi et al., 2012; Miller & Blair, 2009; Perez-Verdin et al., 2008), 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. 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.

Historically, regional economic analysis using input–output modeling has 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 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.

2.2 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. The data was 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 biomass annually (Chen et al., 2010). Table 1 shows the estimated total biomass available for each county, as well as the output of biochar for different conversation rates.

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% and 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 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 USA ranges from $899 to $2,778 per ton. In a study about biomass to biochar and methanol profitability by Shabangu et al., 2014, 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 USA 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

Table 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

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 2.

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 the Supplementary Material .

2.3 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 started 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

Table 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

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 these 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 Results and discussion

3.1 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 1 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) that 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 Fig. 1, even in regions where biochar production does not occur, we can observe the presence of indirect and induced effects.

Results reported in Table 3 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.

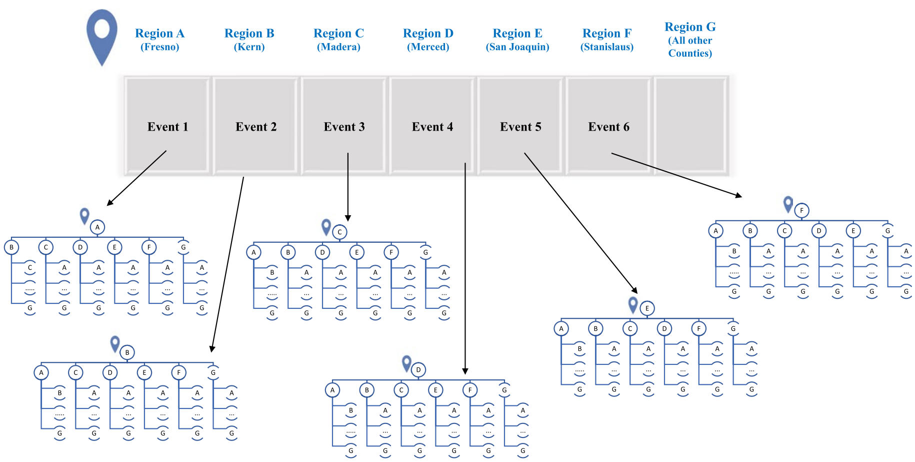

Fig. 1 Direct, indirect, and induced impacts of biochar production. Each region except Region G will have a specific event (biochar production)

Table 3 Total economic impacts of biochar production in six counties (Fresno, Kern, Stanislaus, Merced, Madera, and San Joaquin)

(1) Combination	(2) Activity	(3) Direct impacts	(4) Indirect impacts	(5) Induced impacts	(6) Total impacts	(7) Total SAM multiplier
$80 per ton and conversion rate of 15%						
	Employment	12.00	0.98	3.60	16.58	1.38
	Labor income ($)	1,071,753.06	70,187.85	175,204.40	1,317,145.31	1.23
	Total value added ($)	−514,775.3	93,359.59	344,136.58	−77,279.14	0.15
	Output ($)	72,372.49	196,877.02	567,738.32	836,987.83	11.56
$80 per ton and conversion rate of 25%						
	Employment	12.00	1.03	3.62	16.65	1.39
	Labor income ($)	1,071,753.06	72,717.37	176,101.81	1,320,572.25	1.23
	Total value added ($)	−493,745.71	101,574.48	345,883.70	−46,287.53	0.09
	Output ($)	120,620.81	207,073.83	570,616.52	898,311.15	7.45
$80 per ton and conversion rate of 35%						
	Employment	12.00	1.07	3.64	16.71	1.40
	Labor income ($)	1,071,753.06	76,618.88	177,275.59	1,325,647.54	1.24
	Total value added ($)	−472,715.6	102,209.70	348,176.10	−22,329.81	0.05
	Output ($)	168,869.15	214,929.22	574,410.08	958,208.45	5.67
$280 per ton and conversion rate of 15%						
	Employment	12.00	0.98	3.63	16.61	1.38
	Labor income ($)	1,071,753.06	69,836.38	176,759.57	1,318,349.01	1.23
	Total value added ($)	−333,844.59	92,977.12	347,163.34	106,295.88	−0.32
	Output ($)	253,303.71	195,291.14	572,705.04	1,021,299.89	4.03
$280 per ton and conversion rate of 25%						
	Employment	12.00	1.03	3.67	16.70	1.39
	Labor income ($)	1,071,753.06	73,397.50	178,864.54	1,324,015.11	1.24
	Total value added ($)	−192,193.68	97,585.68	351,267.34	256,659.35	−1.33
	Output ($)	422,172.84	204,740.63	579,461.82	1,206,375.29	2.86
$280 per ton and conversion rate of 35%						
	Employment	12.00	1.08	3.72	16.79	1.4
	Labor income ($)	1,071,753.06	76,772.30	181,053.70	1,329,579.06	1.24
	Total value added ($)	−50,542.77	102,617.19	355,542.49	407,616.92	−8.06
	Output ($)	591,041.98	215,477.89	586,509.34	1,393,029.22	2.35
$2,512 per ton and conversion rate of 15%						
	Employment	12.00	1.00	3.99	16.99	1.42

Table 3 (continued)

(1) Combination	(2) Activity	(3) Direct impacts	(4) Indirect impacts	(5) Induced impacts	(6) Total impacts	(7) Total SAM multiplier
	Labor income ($)	1,071,753.06	70,928.67	194,724.70	1,337,406.43	1.25
	Total value added ($)	1,685,347.81	94,467.66	382,179.99	2,161,995.46	1.28
	Output ($)	2,272,496.11	198,442.21	630,259.12	3,101,197.43	1.36
$2,512 per ton and conversion rate of 25%						
	Employment	12.00	1.06	4.28	17.34	1.44
	Labor income ($)	1,071,753.06	75,018.11	208,700.51	1,355,471.68	1.26
	Total value added ($)	3,173,127.02	100,118.88	409,455.83	3,682,701.74	1.16
	Output ($)	3,787,493.54	210,708.20	675,064.89	4,673,266.6	1.23
$2,512 per ton and conversion rate of 35%						
	Employment	12.00	1.13	4.56	17.69	1.47
	Labor income ($)	1,071,753.06	79,351.31	222,732.32	1,373,836.70	1.28
	Total value added ($)	4,660,906.18	106,073.42	436,815.69	5,203,795.30	1.12
	Output ($)	5,302,490.93	223,648.63	720,003.48	6,246,143.04	1.18

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.

As shown in Table 3, 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, 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. 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 stimulate 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 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 socio-economic context.

3.2 Economic impacts of biochar production by counties in Central Valley, California

Table 4 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 Fresno County), the results will exclusively display the cumulative impact within Fresno County. In this study, six distinct events are being examined (we assumed we have six biochar production facilities). By selecting the Region filter, the analysis will specifically present the combined effects on Fresno County that are attributable to all six events considered in the study.

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. . Biochar enterprise is estimated to create a range of 2.39 to 3.10 new full- and part-time jobs per county annually. 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 significantly benefit from the creation of new jobs in all Central Valley counties. Particularly notable 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 Fresno County 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

Table 4 The total effects on each county when biochar price is $2512 per ton and conversion rate of 15%

(1) Combination	(2) Impacts	(3) Direct impacts	(4) Indirect impacts	(5) Induced impacts	(6) Total impacts	(7) Total SAM multiplier
Fresno County						
	Employment	2.00	0.23	0.87	3.10	1.55
	Labor income ($)	165,945.86	16,568.63	43,139.29	225,653.78	1.40
	Total value added ($)	520,299.02	23,537.01	83,614.61	627,450.64	1.21
	Output ($)	622,536.92	52,416.41	141,316.02	816,269.36	1.31
Kern County						
	Employment	2.00	0.15	0.69	2.84	1.41
	Labor income ($)	193,489.52	12,409.03	32,651.78	238,550.34	1.23
	Total value added ($)	293,842.26	17,841.18	65,127.23	376,810.67	1.28
	Output ($)	391,937.24	37,381.22	107,292.81	536,611.28	1.37
Madera County						
	Employment	2.00	0.11	0.28	2.39	1.20
	Labor income ($)	101,635.21	8,612.04	14,253.10	124,500.34	1.22
	Total value added ($)	117,641.95	10,066.90	28,375.90	156,084.79	1.33
	Output ($)	212,513.43	20,483.10	47,271.51	280,268.04	1.32
Merced County						
	Employment	2.00	0.13	0.62	2.75	1.38
	Labor income ($)	212,919.94	8,807.73	281,27.72	249,855.40	1.17
	Total value added ($)	237,934.48	11,190.43	56,116.76	305,241.67	1.28
	Output ($)	335,006.66	24,091.42	94,336.13	453,434.21	1.35
San Joaquin County						
	Employment	2.00	0.16	0.70	2.86	1.43
	Labor income ($)	209,502.52	12,295.18	34,135.27	255,932.97	1.22
	Total value added ($)	164,870.90	15,185.69	67,638.83	247,695.42	1.50
	Output ($)	260,606.41	28,452.60	108,672.57	397,731.58	1.53
Stanislaus County						
	Employment	2.00	0.21	0.84	3.05	1.52
	Labor income ($)	188,260.02	12,236.04	42,417.53	242,913.59	1.29
	Total value added ($)	350,759.20	16,646.42	81,306.65	448,712.27	1.28
	Output ($)	449,895.45	35,617.46	131,370.07	616,882.98	1.37
All other counties in California						
	Employment	–	0.06	0.68	0.74	–

Table 4 (continued)

(1) Combination	(2) Impacts	(3) Direct impacts	(4) Indirect impacts	(5) Induced impacts	(6) Total impacts	(7) Total SAM multiplier
	Labor income ($)	–	5,826.66	50,838.37	56,665.02	–
	Total value added ($)	–	9,581.78	90,075.83	99,657.61	–
	Output ($)	–	17,829.45	147,838.31	165,667.76	–

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, 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. 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 4 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.

4 Conclusion and policy implications

This study 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 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 credible 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. 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 USA and other regions with a biomass problem.

While our study primarily focuses on estimating regional economic impacts in Central Valley, California, it is 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 is 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 study, 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 study 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 plausible, 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.

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Data availability The data used in the current study are available within the IMPLAN software for the US state of California. The codes are available as supplementary material.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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