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Research article

Reducing energy and carbon footprint in semi-arid irrigated cropping systems through crop diversification

Dabit Bista [a], Sushil Sapkota [a], Pramod Acharya [b], Ram Acharya [a], Rajan Ghimire [b,c,*]

[a] New Mexico State University, Department of Agricultural Economics and Agricultural Business, Las Cruces, NM, USA
[b] New Mexico State University, Agricultural Science Center, Clovis, NM, USA
[c] New Mexico State University, Department of Plant and Environmental Sciences, Las Cruces, NM, USA

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ABSTRACT

Energy and carbon (C) footprints of agricultural production practices have garnered high attention due to rising energy costs and increasing global warming. However, the contribution of conservation and regenerative farming practices, including cover cropping, on energy and C footprints have not yet been documented for cropping systems in arid and semi-arid regions. This study evaluated the energy and C footprint of cover crop integrated silage maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) production systems in the semi-arid region of the southwestern US. The treatments were mixtures of winter cover crops: i) grasses and legumes (GL), ii) grasses, brassicas, and legumes (GBL), iii) grasses and brassicas (GB), and iv) no cover crops (NCC) control for each crop production system. Results showed cover crops had 24.1–24.5% greater energy input than NCC. In silage maize rotation, energy output was 17–22% greater in GBL and GL than in NCC. In silage sorghum rotation, the energy output was 15–24% greater in all cover crops than in NCC. The resulting net energy was 16–21% greater in GBL and GL than in NCC under silage maize, while it was 18–24% greater in GBL and GB than in NCC under silage sorghum. In the silage maize system, the C-footprint per kg yield was not different among treatments, whereas in silage sorghum, it was 58% greater in GBL than in NCC. The benefit-to-cost ratio was greater than one for all treatments, but the additional revenue through C credit programs could make cover cropping a more feasible and beneficial approach, improving economic and environmental sustainability while producing silage crops. While the C footprint was crop rotation specific, cover cropping should be encouraged over crop-fallow systems to producers in semi-arid environments to reduce energy usage and increase C-credit benefits. Clear national and state policy on the C credit program will also enhance economic and environmental benefits by adopting cover cropping and other regenerative farming practices.

1. Introduction

The 2015 Paris Climate Agreement set the goal of limiting global warming below 2 °C by 2100 compared to pre-industrial levels [1]. Agriculture, forestry, and other land uses account for more than 24 percent of the total GHG emissions [2]. The GHG emissions via natural processes are inevitable, but anthropogenic GHG emissions can be substantially reduced through innovations in agriculture [3]. Designing agricultural systems that minimize soil disturbance and maximize ground cover can mitigate global warming by

* Corresponding author. 2346 State Road 288, Clovis, NM, 88101, USA.
E-mail address: rghimire@nmsu.edu (R. Ghimire).

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reducing GHG emissions [4]. In addition, increasing cropping intensity and diversity and minimum soil disturbance enhance climate resilience through SOC sequestration [5,6]. More research is needed on agricultural strategies to mitigate GHG emissions and SOC sequestration, specifically in water-limited environments of arid and semi-arid regions where water is the main driver for SOC and nutrient cycling [7].

Developing climate-smart agricultural strategies involves accounting for both direct and indirect emissions. One of the approaches to reducing indirect GHG emissions from agriculture involves improving energy use efficiency [8]. Energy efficiency has been emphasized in recent years since energy consumption has increased due to population growth and higher living standards. Enhancing energy efficiency while fulfilling the demand for agricultural produce to feed the growing world population could greatly benefit agriculture because unsustainable energy usage has a big share of production costs and environmental footprints of cropping systems [9]. Conventional agriculture often relies on fossil fuels that have low energy efficiency [10]. However, continuous decline in supply and accessibility to fossil fuels, increasing energy costs, and implementing laws to meet GHG emission targets and ecological standards have added challenges to conventional crop production, emphasizing the need for implementing energy-efficient production systems [11]. Most energy is consumed off the farm during input production and transportation, and the consumption can vary with management strategies, such as tillage, crop rotation, and cropping intensity [12]. Therefore, crop selection and optimizing farming practices are vital in sustaining agricultural production in the high energy-demanding global market.

Cover cropping has recently been promoted to enhance agricultural sustainability and climate resilience. Integrating cover crops in crop rotations diversifies cropping systems, reduces fallow periods between crops, and increases residue inputs, improving resource use efficiency and minimizing ecological footprints [13–15]. Cover crops can increase solar energy collection, enhance C flow into the soil, maintain soil microbial habitat, and provide other ecosystem services [16]. Cover crops improve soil quality by increasing organic C content, cation exchange capacity, aggregate stability, and water infiltration [17–20]. Cover crops also enhance N use efficiency, reduce nitrate leaching, suppress pests and diseases, recycle nutrients, control weeds, optimize resource utilization, and reduce energy and costs associated with pesticides and fertilizers [16,21,22]. Compared to single-species cover cropping, using a grass-legume or grass-brassica mixture may control weeds and economically benefit the system [23,24]. Cover crop mixtures can also impact soil C and N dynamics and the system's overall C footprint by adding residue C input [25]. However, their impacts on C and energy footprints have not been studied yet.

Maize (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench] are two major forage crops commonly used in the US dairy industry [26]. Compared to other forage crops, maize produces a high yield of energy-rich forage while requiring less labor and equipment [27,28]. While sorghum is a drought-resilient crop adaptable to a wide range of agronomic and climatic circumstances with decent yield potential [29,30], maize produces high grain yields, has high digestible nutrients, and needs a large amount of water and nutrients [29]. Maize and sorghum are valuable crops for feeding livestock in water-limited areas, but they are exhaustive in soils, and the production system is energy intensive. In addition, there is a trade-off: maize silage often has more digestible energy than sorghum silage due to its high grain content, and sorghum can be grown even in water-limited conditions [31]. However, how cover crop integration influences these crops' energy and C footprints, their feasibility in arid and semi-arid regions and the economic viability of cover crop integrated cropping systems are still debated. Integrating cover crops in silage cropping systems could reduce the C footprint of the production system while improving environmental and energy efficiencies [32,33]. However, no studies investigated the impact of cover cropping on energy and C footprint, particularly in semi-arid silage production systems.

The overall goal of this study was to reduce energy and C footprint in diversified semi-arid irrigated cropping systems. A maize and sorghum silage production system with and without cover cropping was evaluated to gain insights into increasing energy use efficiency (EUE) and C footprint while maintaining crop production. We hypothesized that cover cropping would increase energy efficiency, minimize C footprint, and increase the benefit-to-cost (B/C) ratio of maize and sorghum production systems compared to production systems without cover cropping.

2. Materials and methods

2.1. Study site, treatments, and crop management details

The field study was conducted at New Mexico State University Agricultural Science Center at Clovis, New Mexico (34°35ꞌ N, 103°12ꞌ W, elevation 1368 m). The experimental site had the average maximum and minimum air temperatures of 22.1 and 5.5 °C in 2019, 22.7 and 5.9 °C in 2020, and 22.0 and 5.9 °C in 2021, respectively. The total growing season precipitation was 481 mm, 451 mm, and 360 mm in 2019, 2020, and 2021, respectively. Precipitation did not fulfill crop requirements; thus, the plots were irrigated with 327 mm, 592 mm, and 480 mm water in 2019, 2020, and 2021, respectively.

The study had a randomized complete block design of four treatments and four replications within each crop (silage maize and sorghum) in rotation. Treatments were no cover crop (NCC) control and winter cover crop mixture of grasses, brassicas, and legumes (GBL), grasses and brassicas (GB), and grasses and legumes (GL) in both corn and sorghum phases of crop rotation. Grasses included annual ryegrass (*Lolium multiflorum* Lam.) and winter triticale (× *Triticosecale* Wittmack), brassicas included turnips (*Brassica rapa* subsp. *rapa* L.) and daikon radish (*Raphanus sativus* var. *longipinnatus* Bailey), and legumes were Austrian winter pea (*Pisum sativum* subsp. *arvense* L.) and berseem clover (*Trifolium alexandrinum* L.). The individual plot size was 12.2 m × 9.1 m.

Cover crops mixtures were planted in the third week of September and terminated each year in the last week of April. Cover crops were planted using a double-disc drill opener (Model 3P600, John Deere, Great Plains Manufacturing) calibrated to plant seeds at a depth of 2 cm and a row spacing of 15 cm. The seeding rate was variable among treatments (Table S1) to accommodate approximately the same plant population of diverse species in the mixtures. The cover crops were terminated three to four weeks before planting the main crops using a mixture of herbicides. A mixture of herbicides, including Roundup [*N*-(phosphomethyl glycine (48.7% a.i.)] at 3.5 L ha^{-1}, Panther SC [Flumioxazin (44% a.i.)] at 0.15 L ha^{-1}, First Shot [Thifensulfuron-methyl (25% a.i.)], [Tribenuron methyl (25% a.i.)] at 0.04 L ha^{-1} Detonate [Diglycoamine salt of 3,4-dicholoro-o-anisic (58% a.i.)] at 1.7 L ha^{-1}, Atrazine [Atrazine (42% a.i.)] at 1.7 L ha^{-1} were used for cover crop termination. A second mixture of herbicides comprised of Buccanerr [phosphomethyl glycine (41% a.i.)] at 4.7 L ha^{-1}, Sharpen [saflufenacil (29.7% a.i.)] at 0.11 L ha^{-1}, and Warrant [acetochlor (33% a.i.)] at 4.7 L ha^{-1} was applied before planting the main crop for post and pre-emergence weed control.

Silage maize and sorghum were planted in the third week of May and harvested in the second week of September. Maize variety 'P1828AM' and sorghum silage variety 'Opal' were used in 2019 and 2020, and sorghum silage variety 'Pearl' was planted in 2021 due to emergence issues of Opal seeds in the first two years. Maize and sorghum were planted using a four-row John Deere MaxEmerge planter (Deere and Company, Moline, IL, USA) with a seeding rate of 61,776 maize seeds ha^{-1}, planting depth of 5 cm and row spacing of 76 cm for maize. The row spacing for sorghum was the same as maize, with a targeted plant population of 123,553 ha^{-1}. In the first two years of the study, the silage crops were fertilized with 171 kg N ha^{-1}, 41 kg ha^{-1} P_2O_5, 29 kg S ha^{-1}, and 7.0 L ha^{-1} of chelated zinc (9%) based on the soil test recommendation. However, in the third year, they were fertilized with 224 kg N ha^{-1}, 56 kg P_2O_5 ha^{-1}, 38 kg S ha^{-1}, and 7 L ha^{-1} chelated zinc to meet the crop nutritional demand. The crops were irrigated through a center-pivot irrigation system (Model 9500P, Lindsay Corporation). Silage crops were harvested using a 3960-pull type chopper and a 716-A wagon attached to it, along with a 6430 John Deere tractor.

2.2. *Energy estimate*

Both direct and indirect energy inputs to produce maize and sorghum were evaluated. The direct form of energy input included the energy equivalent of gasoline used to run a tractor. In contrast, indirect forms of input energy encompassed the energy used for manufacturing equipment and producing crops, such as fertilizers, herbicides, insecticides, irrigation, labor, and seeds. This estimate disregarded the contribution of solar energy. A detailed record of all inputs (seeds, fertilizers, agrochemicals, fuel, labor, and machinery power) was maintained and methodically categorized to determine the energy input of each treatment. By multiplying inputs with the conversion coefficients, energy inputs were calculated from physical units to energy units (Table S2). The following equation (Eq 1) was used to determine the indirect energy use of agricultural machinery [34].

$$E_{im} = \frac{MTR \times M}{L \times C_e} \tag{1}$$

where E_{im} is machinery energy input (MJ kg^{1}), MTR is the energy used to make, transport, and repair machinery (e.g., 76 MJ kg^{-1} for tractor and 111 MJ kg^{-1} for other farm machinery); M is the mass of machinery (kg); L is expected life of machinery (in hours); C_e is the effective field capacity of farm machinery (hour). The fuel consumption for chemical applications was estimated using implements pulled by a 170 HP tractor. Manual labor input was converted into energy terms by using a conversion factor.

The following equation (Eq 2) was used to determine the energy needed to pump water from a well [34–37].

$$DE = r \times g \times H \times \frac{Q}{Ep} \times Eq \tag{2}$$

where DE is direct energy (MJ ha^{-1}), r is water density (1000 kg m^{-3}), g is gravitational force (9.80 m s^{-2}), H is the total dynamic head (m), Q is the amount of water needed for one season (m^3 ha^{-1}), Ep is pump efficiency, and Eq is the overall power conservation efficiency. For estimating irrigation energy, transmission, and production efficiencies were also considered.

The fresh yield of maize and sorghum silage was obtained from a 3.47 m^2 area, and the dry matter yield was then estimated by oven drying a subsample at 65 °C until a constant weight was achieved. Average dry matter yields of maize and sorghum were used to calculate output energy. The dry matter silage yields were multiplied with the associated energy coefficients to determine energy outputs [38]. The efficiency of maize and sorghum production was assessed in terms of net energy output (i.e., total energy output minus total energy input) and energy ratio (total output energy divided by total input energy) [39–43] (Table S3).

2.3. *Carbon footprint estimate*

The boundary for C footprint included upstream and indirect emissions (kg C ha^{-1}) from agricultural inputs (irrigation, fertilizers, pesticides, and herbicides application, planting and harvesting, and tillage), direct emissions through soil respiration and N_2O emissions, and net primary productivity for both cover crops and cash crops. The total soil respiration (soil + root respiration) and N_2O fluxes were monitored using EGM-5 (PP Systems Inc.) and Mira-PICO analyzers (Aeries Technologies Inc.), respectively, explained in detail by Acharya et al. [25]. Soil heterotrophic respiration was calculated by multiplying total soil respiration by 0.31 [44], whereas N_2O emissions were expressed in terms of C-equivalents by multiplying the emissions value with a global warming factor of 310 and a conversion to C equivalence [2]. The different C footprint indices were estimated by using the following equations (Eq. 3-5) indicated in Manoj et al. [45]:

$$\text{Net C gain } (\text{kg C ha}^{-1}) = \text{Total C output } (\text{kg C ha}^{-1}) - \text{Total C input } (\text{kg C ha}^{-1}) \tag{3}$$

$$\text{C sustainability index (CSI)} = \frac{\text{Net C gain (kg C ha}^{-1})}{\text{Total C input (kg C ha}^{-1})} \tag{4}$$

$$\text{C footprint per kg silage yield (kg C ha}^{-1}\text{)} = \frac{\text{Total C input (kg C ha}^{-1})}{\text{Annual crop yield (kg C ha}^{-1})} \tag{5}$$

where the total output (kg C ha^{-1}) = sum of C yield in terms of above- and belowground biomass for cover crops and cash crops, but this does not include changes in SOC and input through rhizodeposits. The C content in cash crop and cover crop biomass was considered as 40 % [46,47], while the shoot-to-root ratio for cover crops (1.7) and cash crops (4.7) was considered based on Bolinder et al. [48]. Similarly, total input (kg C ha^{-1}) = all direct and indirect emissions in terms of C-eq. (Supplementary Table S3). A positive value of net C gain indicates the cropping system to be C-deficit (possibly storing C in soil), while a negative value indicates the cropping system losing C in the atmosphere.

2.4. Benefit-cost ratio calculations

The economic feasibility of the cropping system with and without cover crops for both silage crops was assessed by comparing benefit-to-cost ratios (B/C ratio; Eq. (6)) as used by Barut et al. [49] and Pishgar-Komleh et al. [9].

$$\text{B} \Big/ \text{C ratio} = \frac{\text{Total Revenue (US \$ per ha)}}{\text{Total Expenditure (US \$ per ha)}} \tag{6}$$

where total revenue is US $ amount of the final products (i.e., silage yield) and the total expense is US $ amount invested for all the inputs.

The C market is growing in the US, and some private agencies and government programs are starting to buy C credits from the farmers based on per ton of C stored [50]. Therefore, the net benefit of C credit was calculated using C footprint data for 2019 and 2020. There is a high variation in C price among companies; $20 per ton of stored C was used in this study based on the report by Clay et al. [51].

Table 1
Effect of cover cropping on energy variables for maize and sorghum silage production (2018–2021).

	Biomass yield[b]	Energy Input	Energy Output	Net Energy	Output/Input Ratio
	Mg DM ha^{-1}	GJ ha^{-1}			
Cover crop-silage maize					
Treatment					
NCC	25.2 ± 1.3b[a]	31.5 ± 1.7b	473 ± 24b	442 ± 24b	15.13 ± 0.92a
GBL	29.3 ± 1.4a	39.2 ± 1.7a	552 ± 26a	513 ± 26a	14.16 ± 0.79a
GB	28.5 ± 1.3a	39.1 ± 1.7a	536 ± 23 ab	497 ± 23 ab	13.76 ± 0.73a
GL	30.6 ± 1.7a	39.2 ± 1.7a	576 ± 32a	537 ± 32a	14.75 ± 0.89a
Year					
2018–2019	24.1 ± 1.2b	35.5 ± 1.9b	459 ± 22c	423 ± 22b	12.94 ± 0.60b
2019–2020	27.5 ± 0.8b	40.7 ± 1.9a	517 ± 14b	476 ± 13b	12.70 ± 0.28b
2020–2021	33.4 ± 0.7a	35.6 ± 1.9b	627 ± 13a	592 ± 13a	17.71 ± 0.30a
ANOVA (*P*-values)					
Treatment (T)	0.001	<0.0001	0.0023	0.0056	0.2282
Year (Y)	0.001	<0.0001	<0.0001	<0.0001	<0.0001
T × Y	0.924	1	0.9531	0.9531	0.9629
Cover crop-silage sorghum					
Treatment					
NCC	26.5 ± 1.4b	31.8 ± 1.8b	478 ± 25 b	446 ± 25 b	14.95 ± 0.61 a
GBL	31.4 ± 1.2a	39.5 ± 1.8a	565 ± 22 a	525 ± 22 a	14.33 ± 0.59 a
GB	32.8 ± 1.1a	39.6 ± 1.8a	591 ± 20 a	552 ± 19 a	14.94 ± 0.42 a
GL	30.4 ± 1.3a	39.6 ± 1.7a	548 ± 23 a	508 ± 23 ab	13.87 ± 0.59 a
Year					
2018–2019	28.0 ± 1.2b	34.1 ± 2.0b	503 ± 21 b	469 ± 20 b	14.68 ± 0.41 a
2019–2020	28.9 ± 1.2b	39.3 ± 2.0a	519 ± 22 b	480 ± 22 b	13.26 ± 0.57 b
2020–2021	34.1 ± 0.5a	39.2 ± 2.0a	613 ± 90 a	574 ± 80 a	15.62 ± 0.20 a
ANOVA (*P*-values)					
Treatment (T)	0.008	<0.0001	0.0004	0.0011	0.3020
Year (Y)	<0.0001	<0.0001	<0.0001	<0.0001	0.0009
T × Y	0.157	0.25	0.1523	0.1525	0.1563

[a] Mean values (±standard error) followed by different lowercase letters in a column indicate significant differences among treatments and study years ($P \leq 0.05$; Tukey's HSD test). GBL = grasses + brassicas + legumes, GB = grases + brassicas, (GL) = grasses + legumes, NCC = no cover crop.
[b] The original data for biomass yield for 2018–2020 is also available in Acharya et al. [25].

2.5. Statistical analysis

The C and energy measures were first examined to ensure the normality of residuals and equality of variance. All the residuals were normally distributed based on the Shapiro-Wilk test. Only the variables under the direct control of farmers have been considered as energy inputs in this study. Data from 2019, 2020, and 2021 were analyzed separately using the Analysis of Variance (ANOVA) procedure. The dependent variables include energy output, net energy output (energy output-energy input), and energy output to input ratio (output energy/input energy). Similarly, C footprint indices such as C-input, C-output, C-gain, C-footprint per kg yield, and C sustainability index were also analyzed using the same protocol. A pairwise comparison of means for treatments and year was conducted using Tukey's HSD (honestly significant difference) test at $p < 0.05$ in R Studio (http://www.rstudio.com). The energy efficiency analysis was conducted for maize and sorghum separately and together as a combined production system using Stata 18. In addition, three regression models were used to analyze energy efficiency in producing maize, sorghum, and combined crops with different cover crop treatments (defined as dummy variables that take a value of 1 for each treatment and 0 otherwise) relative to no cover cropping and time effect. The combined model measures the effects of different cover crop treatments on net energy output when maize and sorghum are treated as a single crop. Meanwhile, the fourth model compares the energy efficiency of the maize silage production system relative to sorghum (sorghum was used as a dummy; 0 for maize and 1 for sorghum), keeping different cover crop treatments and time effects constant.

3. Results

3.1. Silage yield, energy input, energy output, net energy, and output-to-input energy ratio

Silage maize biomass yield was significantly greater (13–22%) with cover crops than with their absence, leading to a significant difference in energy input, output, and net energy (Table 1). The energy input was at least 24% greater for all cover crop mixtures than for NCC. The energy output under GB (536), GBL (552), and GL (576) were 13%, 17%, and 22% greater than under NCC. Similarly, net energy balance (total output − total input) was 12%, 16%, and 21% greater under GB, GBL, and GL, respectively, than under NCC, while no significant treatment differences were observed for the output-to-input ratio. Comparing the study years, maize yield in 2019–2020 was similar to 2018–2019, but the yield in 2020–2021 was 37% and 21% greater than in 2018–2019 and 2019–2020, respectively. The energy input in 2019–2020 was 15% greater than in 2018–2019, whereas it again decreased by 12.5% in 2020–2021 than in 2019–2020 (Table 1). Compared to 2018–2019, the energy output was 13% and 37% greater in 2019–2020 and 2020–2021, respectively. Similarly, the net energy output in 2020–2021 was 40% and 24% greater than in 2018–2019 and 2019–2020, respectively. Correspondingly, the output-to-input ratio in 2020–2021 was 37% and 39% greater than in 2018–2019 and 2019–2020, respectively. However, there was no significant treatment × year interaction effect on energy input, energy output, net energy output, and output-to-input ratio.

The sorghum silage yield varied among treatments, showing 15–24% greater yield under cover crops than under NCC (Table 1). Therefore, energy input, output, and net output also varied significantly. Compared to NCC, the cover crop treatments had 24.2–24.5% greater energy input use and 18–28% greater corresponding energy output. The net energy output in GL, GBL, and GB was 14%, 18%, and 24%, respectively, greater than in NCC. Comparing among years, sorghum silage yield in 2020–2021 was 22% and 18% greater than in 2018–2019 and 2019–2020, respectively, and all energy estimates differed among the study years (Table 1). The energy input required in 2019–2020 and 2020–2021 were 15.2 and 15.0%, respectively, greater than in 2018–2019. The total and net energy output

Table 2
Energy efficiency model results using regression analysis.

Treatment	Maize	Sorghum	Combined	Crop Impact
GL	94.78***	62.17**	78.47***	78.47***
	(27.89)	(26.9)	(19.24)	(19.56)
GBL	70.6***	79.23***	74.92***	74.92***
	(23.23)	(27.42)	(17.72)	(17.78)
GB	54.73**	105.79***	80.26***	80.26***
	(21.49)	(23.13)	(16.29)	(16.03)
Time trend	84.16***	52.14***	68.15***	68.15***
	(12.09)	(8.71)	(7.53)	(7.53)
Sorghum				10.7
				(13.39)
Constant	273.59***	341.54***	307.57***	302.22***
	(33.7)	(26.93)	(20.93)	(22.37)
Number of observations (n)	48	48	96	96
R-squared	0.64	0.46	0.51	0.51

Note: The net energy output was converted to 1000 GJ before estimating the model, and the estimated parameters should be interpreted accordingly. Variables are defined as follows: GBL is a cover crop mix of grasses, brassicas, and legumes, GB = is a cover crop mix of grasses and brassicas, and GL = is a cover crop mix of grasses and legumes, NCC = no cover crop.
Numbers in parenthesis are robust standard errors.
***$p < 00.01$, **$p < 00.05$, *$p < 00.1$.

were 18–22% and 20–22% greater, respectively, in 2020–2021 than in the first two years of the study. However, the output-to-input ratio in 2019–2020 decreased by 10% more than in 2018–2019, whereas it increased in 2020–2021 by 18% more than in 2019–2020. However, there was also no significant treatment × year interaction for energy input, energy output, net energy, and output-to-input energy ratio (Table 1).

Net energy efficiency estimation by four different regression models showed the R-square values, generally used to measure goodness of fit, ranged between 0.46 and 0.64, indicating a good fit of the estimated models. All model parameters were statistically significant except for the dummy variables in sorghum, which controls the crop effect in the last model and carries positive signs indicating their positive impact on net energy output. A time variable included in models to examine whether the net energy output efficiency changes over time shows an increase in net energy output efficiency by about 68,150 GJ per year during the study period (Table 2). With this, the net energy output from GB was 54,730 (i.e., 54.73 × 1000) GJ greater than from NCC. The net energy output from GBL and GL cropping systems was 70,600 GJ ha^{-1} and 94,78 GJ ha^{-1}, respectively, higher than from NCC. Likewise, all sorghum silage production systems incorporating cover crops were more net energy efficient than NCC. The net energy output from GL, GBL, and GB was significantly greater than that from NCC by 62,170, 79,230, and 105,790 GJ ha^{-1}, respectively. The results from the last model showed that, on average, GL, GBL, and GB cropping systems generated more net energy outputs than NCC by 78,470, 74,920, and 80,260 GJs ha^{-1}, even after controlling for crop effects and the time trend.

3.2. Carbon inputs, outputs, and C footprint indices in cover crop integrated silage systems

In the silage maize system, there was no significant treatment × year interaction for C-input, C-output, C-footprint, CSI, and C-

Table 3
Average of C footprint indices in cover crop integrated silage systems.

	Indirect emissions	Direct emissions	C-input	C-output	C-gain	C-footprint per kg yield	C sustainability index
	(kg C-eq. ha^{-1})						
Cover crop-silage maize							
Treatment							
NCC	532	6535	7068 ± 455b[a]	11113 ± 651b	4045 ± 934b	0.32 ± 0.04a	0.64 ± 0.16a
GBL	563	7983	8546 ± 105 ab	17150 ± 815a	8604 ± 127a	0.32 ± 0.04a	1.17 ± 0.24a
GB	563	8716	9279 ± 517a	16157 ± 508a	6878 ± 695a	0.36 ± 0.03a	0.78 ± 0.13a
GL	563	8847	9411 ± 878a	17562 ± 101a	8151 ± 997a	0.34 ± 0.03a	0.95 ± 0.17a
Year							
2018–2019	488	7422	7910 ± 336a	14477 ± 858a	6567 ± 954a	0.34 ± 0.02a	0.89 ± 0.15a
2019–2020	624	8618	9242 ± 701a	16514 ± 754a	7272 ± 647a	0.33 ± 0.02a	0.88 ± 0.11a
ANOVA (*P*-values)							
Treatment (T)			0.054	0.0002	0.022	0.820	0.195
Year (Y)			0.109	0.076	0.540	0.883	0.991
T × Y			0.073	0.833	0.628	0.355	0.245
Cover crop-silage sorghum							
Treatment							
NCC	532	3924	4457 ± 487b	11757 ± 768b	7299 ± 814a	0.19 ± 0.02b	1.86 ± 0.35a
GBL	563	8164	8727 ± 106a	18412 ± 753a	9685 ± 120a	0.30 ± 0.04a	1.52 ± 0.57a
GB	563	6616	7179 ± 122 ab	18984 ± 870a	11805 ± 125a	0.23 ± 0.04 ab	2.39 ± 0.74a
GL	563	6687	7250 ± 558 ab	17573 ± 643a	10323 ± 734a	0.26 ± 0.02 ab	1.52 ± 0.20a
Year							
2018–2019	488	5491	5978 ± 746b	16313 ± 947a	10335 ± 844a	0.21 ± 0.02b	2.34 ± 0.45a
2019–2020	624	7204	7829 ± 620a	17050 ± 860a	9221 ± 762a	0.28 ± 0.02a	1.31 ± 0.15a
ANOVA (*P*-values)							
Treatment (T)			0.039	<0.0001	0.097	0.063	0.587
Year (Y)			0.044	0.330	0.272	0.040	0.061
T × Y			0.785	0.222	0.755	0.958	0.917

[a] Mean(±standard error) followed by different lowercase letters in a column indicate significant differences among treatments and study years ($P \leq 0.05$; Tukey's HSD test). GBL = grasses + brassicas + legumes, GB = grasses + brassicas, GL = grasses + legumes, NCC = no cover crop.

Table 4
Benefit-cost analysis of maize and sorghum under different treatments and years on a per hectare per year basis.

Crop	Treatment[a]	2019			2020			2021			Average
		Expenditure	Revenue	B/C ratio	Expenditure	Revenue	B/C ratio	Expenditure	Revenue	B/C ratio	B/C ratio
		US dollars ($)			US dollars ($)			US dollars ($)			
Maize	NCC	1134	2278	2.01	1278	2556	2.00	1273	3129	2.46	2.16
	GBL	1359	2747	2.02	1503	2972	1.98	1419	3710	2.61	2.20
	GB	1355	2686	1.98	1498	2806	1.87	1414	3619	2.56	2.14
	GL	1373	2774	2.02	1517	3171	2.09	1433	3852	2.69	2.27
Sorghum	NCC	930.6	2198	2.36	1074	2674	2.49	1070	2964	2.77	2.54
	GBL	1155	3178	2.75	1299	2888	2.22	1294	3399	2.63	2.53
	GB	1151	3086	2.68	1295	3341	2.58	1290	3468	2.69	2.65
	GL	1170	3068	2.62	1313	2703	2.06	1308	3370	2.58	2.42

[a] GBL = grasses + brassicas + legumes, GB = grasses + brassicas, GL = grasses + legumes, NCC = no cover crop.

footprint per unit yield (Table 3). Carbon input differed among treatments, where GB and GL had 31–33% greater C-input than NCC. However, C-output was 45–58% greater under cover crop treatments than under NCC. The treatment differences for C inputs and outputs also affected the C-gain of the system, thus resulting in 70–113% greater C-gain under cover crops than in NCC. There were no significant treatment differences in CSI and C-footprint per unit yield for this cropping system. In addition, none of the C footprint indices significantly differed between the study years.

Like the silage maize system, none of the C footprint indices had a significant treatment × year interaction for the silage sorghum system (Table 3). The C-input under NCC was 49% lower than GBL but statistically similar to GB and GL. However, C-output was 49–61% higher in cover crop mixtures than under NCC. Unlike in silage maize, there was no significant treatment effect for C-gain, although cover crops had numerically higher values than the NCC. Also, CSI was not different among the treatments. In cover crop integrated silage sorghum, C-footprint per unit yield showed treatment differences at $P = 0.06$, where GBL had a 59% greater C-footprint than NCC. The main effect of year was significant only for C-input and C-footprint per unit yield. The C-input and C-footprint per unit yield were 31% and 30% greater in 2019–2020 compared to 2018–2019, respectively.

3.3. Benefit-cost and carbon market analysis

The benefit-cost (B/C) analysis for both crops showed a B/C ratio greater than one for all treatments across the study years, indicating the economic feasibility of maize and sorghum production in semi-arid environments (Table 4). The B/C ratio for maize silage systems ranged from 1.98 to 2.02, 1.87 to 2.09, and 2.46 to 2.69 in 2018–2019, 2019–2020, and 2020–2021, respectively. The average B/C ratio was greater for GL (2.27) and GBL (2.20) than NCC (2.16) for the maize silage system, implying that GBL and GL are more economically efficient than NCC. The B/C ratio for the sorghum silage system ranged from 2.36 to 2.75, 2.06 to 2.58, and 2.58 to 2.77 in 2018–2019, 2019–2020, and 2020–2021, respectively. It was greater only for GB (2.65) than NCC (2.54), indicating greater economic efficiency of GB cover cropping than NCC.

Both maize and sorghum silage yields were significantly greater in cropping systems integrating cover crops (Table 1), indicating considerably more C absorption from the environment. If C captured and stored in biomass is incentivized through subsidies or C market exchange similar to one for soil C sequestration, more silage producers will be willing to adopt cover cropping and other conservation practices because cover crops would generate higher benefits than NCC, with the greatest additional benefits ($175 ha^{-1}) with GL in 2019, followed by GBL ($162 ha^{-1}) and GB ($134 ha^{-1}) (Table 5). In the case of sorghum, GB had the highest additional benefit ($248 ha^{-1}) in 2019, followed by GL ($228 ha^{-1}) and GBL ($212 ha^{-1}). The GBL generated the greatest additional benefit ($183 ha^{-1}) in 2020 maize, and GB had the greatest benefit for sorghum ($225 ha^{-1}). Although smaller, there was a positive economic incentive of incorporating cover crops in maize and sorghum silage production. Moreover, a well-functioning C credit market that trades C storage in biomass would motivate silage producers to adopt conservation practices such as cover cropping in their production system.

4. Discussion

4.1. Cover crop improved energy efficiency in cropping systems

The results of this study supported our hypothesis that the total energy output, net energy output, and C gain would be higher in cover crop integrated rotations than in crop rotations without cover crops. The greater energy output with cover cropping was linked to greater cash crop production, showing an input-output balance in both systems. In arid and semi-arid environments where water is the primary driver of crop production [52], cover crop residues serve as a mulch during the cash crop phase of a crop rotation, reduce energy expenses in evapotranspiration and increase energy efficiency [53]. A study from the same experimental site had shown that the cover crop system used 75–94 mm more water than the NCC for their growth, but the overall system water productivity was 29–41% greater with cover cropping than without [54]. These results indicate energy outflows through increased evapotranspiration loss under NCC, while cover-cropped systems exhibit improved water utilization and reduced energy costs. Cover-cropped systems also

Table 5
Net revenue from carbon credit using cover crops in 2019 and 2020.

Crop	Treatment[a]	2019				2020				2019–2020 Average net revenue from carbon credit
		Carbon gain (Mg C ha^{-1})	$ Rate	Revenue	Net revenue from carbon credit	Carbon gain	Amount	Revenue	Net revenue from carbon credit	
Maize	NCC	2.75	$20.0	$55.0	0	5.34	$20.0	$107	0	0
	GBL	8.12	$20.0	$162	$107	9.09	$20.0	$182	$75.0	$91.0
	GB	6.68	$20.0	$134	$79.0	7.10	$20.0	$142	$35.0	$57.0
	GL	8.75	$20.0	$175	$120	7.76	$20.0	$155	$48.0	$84.0
Sorghum	NCC	6.99	$20.0	$140	0	7.61	$20.0	$152	0	0
	GBL	10.6	$20.0	$212	$72.0	8.76	$20.0	$175	$23.0	$47.5
	GB	12.4	$20.0	$248	$108	11.23	$20.0	$225	$73.0	$90.5
	GL	11.4	$20.0	$228	$88.0	9.26	$20.0	$185	$33.0	$60.5

[a] GBL = grasses + brassicas + legumes, GB = grasses + brassicas, GL = grasses + legumes, NCC = no cover crop.

provide other ecosystem services, including weed and insect-pest suppression, soil moisture conservation, and improved soil health [24,25], contributing to increased energy outputs and net energy. As a winter cover crop, brassica species can provide greater canopy cover and enhance nutrient cycling, making them readily available to the main crops [55]. Cover crop treatments that include legumes could have benefitted from atmospheric N fixation, increasing N availability for the succeeding cash crops and improving crop production [18,19]. While input and output energy varied, and the mechanism of soil health and ecosystem services may differ across treatments, the output-to-input energy ratio remained comparable. Among study years, a higher output-to-input energy ratio was achieved in the third year of this study, which can be attributed to increased silage crop yield driven by improved soil conditions through continuous cover cropping.

Maize silage often has more digestible energy than sorghum silage due to its high grain content, making it well adapted for use in low cost rations [31]. However, maize is a highly exhaustive crop needing more water and fertilizer. The high input requirement is compensated with high output production in maize, making the output-input energy ratio similar to sorghum rotation. Sorghum, instead, is better adapted to water-limited conditions because it consumes around 30% less water and needs less N fertilizer than maize for comparable production [56,57]. However, there was an interannual variability in energy output and energy efficiency. The experiment was conducted at the same site and cultivation practices over three years, but significant variations were observed in the amount and distribution of rainfall, which may have caused interannual variation in silage yields and energy balance. Although the cash crop phase of the rotation was irrigated, the amount and timing of precipitation affected the phenological development and the efficacy of chemical fertilizers and nutrients to crops and, ultimately, the energy inputs and outputs. Water is limited in the southern Great Plains of the US, and meeting the evapotranspiration demand of crops during mid-summer, also a peak growth stage of the crop, is challenging. Despite the interannual variability, the cover cropping systems were more energy efficient than NCC in maize and sorghum rotations.

4.2. Carbon footprint of cover cropping systems was related to the variation in carbon output

Cover crops photosynthetically capture atmospheric CO_2 and store it in vegetation or soil. Cover crops integrated silage cropping systems increased residue C inputs, leading to a higher net C gain. In addition, subsequent maize and sorghum yields under cover crops increased C-output. Long-term soil C storage is possible with the added biomass C incorporated into the soil. Cover crop biomass was left on the field for decomposition in this study, but additional biomass production in cash crops was harvested as forage. Increased root biomass in both phases of rotations (cover crops and cash crops) also contributed to SOC sequestration. A complementary study by Acharya et al. [6] reported increased SOC storage after four years of cover cropping compared to NCC. However, cover crops also increased C loss due to higher CO_2 fluxes associated with autotrophic and heterotrophic respiration [25]. Cover crops increase microbial biomass and activity [58,59], releasing CO_2 derived from root respiration compared to its absence in NCC plots. With an increase in both input and output, there was no difference in the C sustainability index. However, increased C inputs and microbial activity under cover cropping increased soil organic C storage [6]. Moreover, greater SOC content fosters improved soil health and indirectly aids in increasing cash crop yields [60]. Among cash crops, more subtle differences in sorghum yield were observed among the years, which could be due to the drought-resilient nature of this crop, making it perform better under stressed conditions than maize. Despite variation in C inputs, outputs, and interannual differences, comparable C footprint among treatments and increased energy efficiency suggest cover cropping as a viable strategy to improve sustainability and climate resilience in semi-arid agroecosystems.

4.3. Economics of cover cropping and policy implications for improving carbon and energy efficiency

The B/C ratio was greater than one for all treatments, signifying the economic viability of using cover crops in silage production systems. Fresh silage prices are generally high in arid and semi-arid regions because of limited production and the recent systemic supply shortage caused by factors such as COVID-19 and the subsequent rise in farm input and fuel prices. Although the cost of production was similar to that of Berti et al. [31], the B/C ratio in our study was almost double (1.2 versus 2.2). The B/C ratio for producing sorghum silage was also greater than previously reported by McCorkle et al. [61]. Nilahyane et al. [62] discussed alternative cropping systems, including cover cropping, to overcome sustainability challenges in water-limited environments of the Great Plains of the USA. Although the cover crop system had additional input cost, the B/C ratio was almost similar to NCC, indicating that incorporating cover crops involves additional expenses but enhances the subsequent crop yield and increases farm profit. In addition, the silage cropping system with cover crops was more energy efficient than the system without cover cropping. Thus, long-term cover cropping in water-limited environments can improve the sustainability of agriculture and increase its resilience to changing climates.

Government subsidy programs such as the Environmental Quality Incentive Program of USDA Natural Resources Conservation Services encourage farmers to adopt cover cropping and other innovative farming practices by providing economic incentives for adopting these practices. Since additional input cost is needed to cover cropping, compensation through additional cash crop yield and government subsidy programs helps farmers adopt these practices. Our study also showed net C gain with cover cropping compared to without. Farmers receiving C credits may also receive additional income by increasing soil C in their farms [51]. This study did not measure soil carbon per se, but net C gain was higher for cover-cropped systems than NCC on studies reported from the same experimental plots [6,63]. The government should increase subsidies for farmers integrating cover crops into the cropping system to promote climate-smart production practices. Promoting the adoption of such practices by providing incentives through C credit programs or other ecosystem services subsidies can motivate silage producers on climate-smart agriculture in arid and semi-arid regions.

5. Conclusion

Integrating winter cover crops in the summer silage production system showed increased energy inputs, energy output, and net energy balance. All three cover cropping systems were energy efficient compared to no cover cropping in terms of net energy output to produce silage crops. Similarly, both C input and output were greater with cover crops than without in both silage crop production systems. In contrast, maize and sorghum production systems were not significantly different regarding energy footprint. The B/C ratio for both crops was higher with cover crops than without cover cropping, and all silage production systems with cover cropping became more profitable than those without cover cropping when C credit was incorporated into the analysis. Additional revenue through C credit programs could make cover cropping a more feasible and beneficial approach for arid and semi-arid regions. Cover cropping should be encouraged over crop fallow systems by developing and implementing state and national policies to support climate smart crop production in arid and semi-arid environments.

Data availability statement

The data used in this paper can be available upon request to the corresponding autor.

CRediT authorship contribution statement

Dabit Bista: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Sushil Sapkota:** Writing – original draft, Investigation, Formal analysis, Data curation. **Pramod Acharya:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Ram Acharya:** Writing – original draft, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Rajan Ghimire:** Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

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