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Quantifying Greenhouse Gas Emissions from Irrigated Rice Production Systems in Ghana

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Abstract

Estimation of the carbon footprint in rice cropping systems can help in identifying the major options available in the quest to reduce greenhouse gas (GHG) emissions in agricultural production. This research study assessed the greenhouse gas emissions of irrigated rice production based on field experiments and surveys. The study determined the effect of application of different nitrogen rates on crop yield, carbon footprint and net carbon in irrigated rice (*Oryza sativa var KRC Baika*) production systems. A three-year (one minor season followed by two major seasons) field experiment was conducted on a Vertisol in a completely randomized design with four nitrogen application rates. Biomass yield and the N content of straw and grain were determined after harvest. Additionally, data on detailed farm activities relative to the cultivation of the rice crop, input use as well as biomass yield were obtained and used to estimate the carbon footprint during the study. The results showed that between 862 and 1717 kg CO_2-eq ha^{-1} was emitted from rice fields per season. From this study, nitrogen fertilizer with about 42% of the emissions, was the biggest contributor to total GHG emissions ha^{-1} of rice crop. Applying nitrogen fertilizer at 90 kg N ha^{-1} gave a similar yield, but with a lower carbon footprint relative to the application of 135 kg N ha^{-1}. Therefore, applying N at 90 kg N ha^{-1} maintained yields, reduced GHG emissions and had a positive net carbon. The results of this study can be applied to ensure that farmers maintain yields with less cost to the environment.

Keywords

Greenhouse Gas, Emissions, Carbon Footprint, Nitrogen Fertilizer, Rice Production

1. Introduction

Interest in greenhouse gas emissions and climate change continues to rise in recent times. Global atmospheric carbon dioxide levels have increased from a pre-industrial value of around 280 ppm to 407.4 ± 0.1 ppm in 2018 according to the "State of the Climate" report from the National Oceanic and Atmospheric Administration (NOAA) and the American Meteorological Society [1]. Since 1979, land temperature has increased by approximately 0.258˚C per decade and sea temperatures by approximately 0.138˚C, and is projected to increase by 1.1 to 1.4˚C respectively by 2100 [2]. Concerns about greenhouse gas (GHG) emissions and their effect on global climate change have inspired the quantification of the carbon footprint in major anthropogenic activities that contribute to carbon emissions. The carbon footprint is the contribution to GHG emissions in carbon equivalents (CE) of any human-related activity. The carbon footprint has become very important because it indicates how a particular activity affects the environment through GHG emissions. Agriculture is known to contribute significantly to global carbon emissions through the use of farm machinery, agrochemicals such as fertilizers and pesticides (herbicides, insecticides and fungicides), which eventually release carbon dioxide and other greenhouse gases into the atmosphere upon their interactions with the environment. During crop production however, carbon dioxide is absorbed by crops through photosynthesis to produce biomass. As such, calculations on a per area basis through estimation of the carbon released from input utilization along with the carbon biologically consumed by the crop can lead to estimation of the net carbon footprint. For example, a positive net carbon balance after all major farm production operations have been assessed, can be an indicator of the efficiency of agricultural production in a particular cropping system. Significant mitigation potential could be derived if improved management options in agricultural production are carried out. Through such studies, we may be able to explore the potential for mitigation of greenhouse gas emissions from food crops and other production systems. As concerns continue to increase regarding human-induced impacts on global climate, detailed studies on the contribution of specific farming activities during crop production to the overall footprint are now being [3] [4] [5].

There is therefore the need to conduct studies to quantify greenhouse gas emissions from the cultivation of major food crops. A breakdown of the effect of each individual activity on the overall footprint is useful in considering how and whether reduction of carbon footprint can be achieved through improved production practices and efficiency of resource use. It is possible that a reduction in agrochemical input use, for instance, can decrease the carbon footprint in addition to having a beneficial effect on the biodiversity within and around arable fields [6] [7] [8].

Rice cultivation has received attention as a crop production system that leads to the emission of three of the most potent greenhouse gases, carbon dioxide, methane and nitrous oxide [9] [10]. Rice has become one of the major crops cultivated in Ghana over the years. Due to its importance, plans have been initiated to increase local rice production to meet the increasing demand. Increased production in the rice crop, which may come with intensification of production operations and increased inputs and resource use, may lead to an anticipated increase in greenhouse gas emissions with methane emission being a major concern. Identifying the carbon footprint of a crop is an important component of sustainable agriculture [11]. This is because, it could identify areas in farm operations and management that could be targeted as options for mitigation. However, very little information exists on the carbon footprint of the various cropping systems, including that of rice in Ghana. A few studies that have been done are based on survey data with very little information on the carbon footprint from actual field experiments. [12] conducted some studies based on surveys and noted that inorganic fertilizer accounted for 72% of the carbon footprint for rice in northern Ghana. The study was however limited to Northern Ghana, where rice production is largely rain-fed with a few irrigation schemes and input use is relatively on a lower scale compared to the intensive irrigated rice production systems in the coastal savanna zone of Ghana. Surveys conducted within the intensively irrigated rice production areas in the coastal savanna zone of Ghana show higher application of nitrogen fertilizer over the recommended application rates. Due to its fundamental role in biomass accumulation during crop growth, nitrogen plays a key role in crop yields [13]. For this reason, some farmers frequently apply excess N in rice production systems as an extra insurance against yield losses from nutrient deficiency [14]. Application of excess N above optimum rates however, has not been demonstrated to proportionally increase grain yield in rice production systems [15]. Together with other farm operations associated with irrigated rice cultivation, the excessive application of nitrogen fertilizer is likely to come with an anticipated increase in greenhouse gas emissions in addition to low nitrogen use efficiency and pollution of soil and water sources [16]. It is therefore important to identify the environmental impact of different management approaches in the intensive irrigated rice production systems in southern Ghana. The objectives of this study therefore, were to quantify the carbon footprint due to farm operations and input use of irrigated rice systems in Southern Ghana and identify N management options that minimize greenhouse gas emissions while optimizing yield.

2. Materials and Methods

2.1. Experimental Site and General Climatic Conditions of the Study Area

The study was conducted at the Soil and Irrigation Research Centre (SIREC) of the University of Ghana at Kpong in the eastern region of Ghana. The site lies in the coastal savannah agro-ecological zone of Ghana (6˚9'N, 0˚4'E) and has an altitude of 22 m above mean sea level. The area experiences a bimodal rainfall pattern, with a mean annual precipitation of approximately 1150 mm. The major season is from March to July and the minor season from September to November. The mean air temperature is 27.2˚C with mean maximum and minimum air temperatures of 33.3˚C and 22.1˚C, respectively. The site has a gentle sloping land with between 2% and 5% gradient and a savanna grassland vegetation with scattered shrubs and trees. Rice in the study area is generally grown in the main crop season (March-June) and minor crop season (August-November) under flooded conditions. Field experiments were conducted from 2015 to 2017 on Akuse series classified as a Typic Calciustert [17], at the Soil and Irrigation Research Centre, Kpong of the University of Ghana, Legon. The texture of the soils generally ranges from sandy clay to clay loams. Synthetic nitrogen fertilizers are predominantly applied with occasional addition of organic manure. Rice straw is normally left in the field after harvest and burnt during land preparation for the next crop. Greenhouse gas emissions therefore occur during the cropping season and upon burning of the straw during land preparation.

2.2. Soil Characterization

The texture of the soil was determined using the Bouyoucos hydrometer method modified by [18]. Determination of the bulk density was done using a core sampler with a known volume to collect undisturbed soil samples. The soil samples were then oven-dried at 105˚C for 48 h and the bulk density was determined by dividing the mass of soil by the volume. Soil pH was determined in water and 0.01 M $CaCl_2$. The organic carbon content of the soil was determined by the wet combustion method of [19], after carbonates were destroyed by the addition of HCl. The total nitrogen content was determined by dry combustion method using a Leco Trumac Carbon Nitrogen Sulphur version 1.3 Analyzer. The available P was extracted by the method of [20]. The concentration of P in the extracts was then determined using the method of [21]. The cation exchange capacity (CEC) of the soil was determined by the ammonium acetate (NH_4OAc, pH 7) method.

2.3. Experimental Design and Treatments

The data used in this study were obtained from both surveys and field experiments. Rice was grown on experimental plots in the 2015 minor season (September-December), 2016 major season (April-July) and 2017 major season (April-July). Nitrogen application rates of 0, 45, 90 and 135 $kg \cdot ha^{-1}$ were used with each treatment plot measuring 9 m by 5 m. All the treatments were replicated four times and arranged in a completely randomized design. A medium duration rice variety, *KRC Baika*, was used as a test crop for this study. Thus, with 4 N application rates, 4 replicates and 1 test crop, there were 16 experimental units which were arranged in a completely randomized design. Average temperature during the growing period was between (23.3˚C and 31.8˚C). After field preparation, which involved puddling and leveling, 21-day old rice seedlings were transplanted with 2 seedlings per hill. The seedlings were transplanted at a spacing of 20 cm within rows and 20 cm between rows in each plot, giving a total plant population of 25 hills/m^{-2}. One week after transplanting, triple superphosphate and muriate of potash were applied at a rate of 45 kg ha^{-1} P_2O_5 and 45 kg ha^{-1} K_2O to all plots as basal nutrients. Half the amount for each N treatment (*i.e.*, 22.5, 45 and 67.5 kg·ha^{-1}) for the 45, 90 and 135 kg·ha^{-1} application rates respectively, were applied together with the P and K fertilizers, one week after transplanting and the other half applied 60 days from the date of emergence at the nursery. Herbicides were used to control the weeds and the crop harvested at 120 days after emergence.

2.4. Plant Analysis and Data Sources

Data were obtained on detailed farm activities relative to the cultivation of the rice crop, input use as well as biomass (straw and grain) yield. An area measuring 7 m × 4 m in the middle of each plot was harvested at maturity and the above ground biomass separated into the grains and straw. The plant material (grain and straw) was dried at approximately 70˚C to a constant weight and milled. Tissue N concentration of the rice straw and grain were subsequently determined by the Kjeldahl digestion procedure outlined by [22].

Primary data were also collected from 40 rice farmers and 10 machinery operators through a survey in the coastal savannah zone of Ghana in 2016. For most local farmers, fields are mostly prepared and harvested with machinery. Seeding of rice is usually done manually and weeds controlled with herbicides. Crop residues are usually burnt before field preparation and fields are flooded intermittently during the cropping season. Activities for machinery operators covered only fuel consumption for operations like ploughing, harrowing, rotovating, harvesting, etc. In total, 50 rice farmers'/machinery operators were interviewed to obtain information on production and energy use. Survey questions covered farm activities, input use, crop yield and other routine farm activities.

2.5. Carbon Footprint Estimation Procedure

The methodology used in the estimation of the carbon footprint followed the Tier 1 procedure of the Intergovernmental Panel on Climate Change [23] and is expressed in the standard unit of carbon equivalent (CE). Conversion factors followed the procedure proposed by [24] [25] [26] and are summarized in **Table 1**.

Carbon fixed in plants (stem and leaves) from the atmosphere was determined by multiplying the corresponding amount of biomass by its percentage carbon content [27] [28]. In this calculation, 1 g of dry biomass contains approximately 0.4 g of carbon. In the determination of the biomass yield only stem and leaves were considered.

Emission factors which are representative values that relate the quantity of equivalent greenhouse gas released to the atmosphere as a result of fuel consumption for the associated farm operations during the production of the rice crop, were determined using [29] conversions. For this determination, the equivalent level of fuel consumption in CO_2, CH_4, and N_2O units are provided in **Table 2**.

Table 1. Conversion factors for carbon equivalent (CEs) estimation.

Input	Equivalent carbon emission (kg CE kg^{-1})
a) *Fertilizer*	
Nitrogen	1.30
Phosphorus	0.20
Potassium	0.15
b) *Pesticides*	
Herbicides	6.30
Insecticides	5.10
Fungicides	3.90
c) *Energy*	
Diesel	0.940
Petrol	0.850
Electricity (*Kw·h*)	0.073

Sources: [24] [25] [26].

Table 2. Emission factors for greenhouse gases during farm operations in rice production.

Compound	Classification factor	Reference
Fuel	1 kg = 6.91 g CH_4	[30]
Fuel	1 kg = 0.02 g N_2O	[30]
Fuel	1 kg = 3150 g CO_2	[30]

For simplification of the determination of total greenhouse gas emission or fixation, all computations were reported as CO_2 equivalent by using IPCC guidelines (**Table 3**). Net carbon estimates were obtained by combining both carbon emissions from field production and carbon fixation through photosynthesis. This study focused on emissions due to farm activities and input use, root biomass was however not considered in these estimates.

The data generated from the experiments were subjected to analysis of variance (ANOVA) using Genstat 12th edition to establish if there were any significant treatment effects at $p < 0.05$. Mean separations were done using Tukey's Lsd (0.05).

3. Results

3.1. Soil Properties

The physical and chemical properties of the soil used for the experiment are shown in **Table 4**. The soil had a sand content of 47.1% in the plough layer (up to a depth of 20 cm). The silt and clay contents were 12.4% and 40.5% respectively. The bulk density of the soil was 1.4 Mg/m^3 with the pH in the neutral range at 7.1. The organic carbon content of 9.1 g/kg was low and the available P

Table 3. Classification factors for greenhouse gas emissions in rice production systems.

Compound	Classification factor	Reference
CH_4	1 kg = 21 CO_2-eq	IPCC, 1997 [31]
CO_2	1 kg = 1 CO_2-eq	[31]
N_2O	1 kg = 310 CO_2-eq	IPCC, 1997 [31]

Table 4. Some physico-chemical properties of the soil used for the field experiment.

Soil properties	Typic calciustert
Sand%	47.1
Silt%	12.4
Clay%	40.5
Texture	Sandy Clay
Bulk density Mg/m^3	1.4
pH_w (H_2O)	7.1
pH_s (0.01 M $CaCl_2$)	6.2
Organic Carbon g/kg	9.1
Total Nitrogen g/kg	0.91
Available Phosphorus mg/kg	8.93
CEC cmol/kg	37.6

content of 8.9 mg/kg also very low. The total N content of 0.91 g/kg was low, although the cation exchange capacity of 37.6 cmol/kg was high.

3.2. Biomass Yield

Generally, biomass yield corresponded with N application rates with treatments receiving N application rates of 135 kg N ha^{-1} having significantly higher biomass yields than the other treatments. At 12,253 kg N ha^{-1} the biomass yield of the treatment that received 135 kg N ha^{-1} was 1.73 and 3.25 folds higher than those that had application of 45 and 0 kg N ha^{-1} respectively.

Although only about a 3% increase in biomass (straw + grain) yield of the 135 kg N ha^{-1} treatment relative to that of 90 kg N ha^{-1} was recorded, the differences observed were significant as shown in Table 5. In the treatments with N fertilizer rates of 90 kg·ha^{-1}, biomass yield increases observed were approximately 1.7 and 3 folds than that of treatments that received 45 kg N ha^{-1} and 0 kg N ha^{-1} respectively. Yields from the 45 kg N ha^{-1} treatment were approximately 1.9 folds more than the control. Biomass yield was in the order (135 > 90 > 45 > 0) kg N ha^{-1}.

Grain yield of rice generally increased with increasing nitrogen application rate, although the yields for 90 and 135 kg N ha^{-1} were not significantly different ($p < 0.05$) over the 3-year period (Table 5). Similar to what was obtained in the biomass yield, application of N at 135 kg·ha^{-1} over the 3-year period did not

Table 5. Mean rice grain yield, straw yield and N content of grain and straw over three years.

N rate ($kg·ha^{-1}$)	Grain yield ($kg·ha^{-1}$)	Straw yield ($kg·ha^{-1}$)	Biomass yield ($kg·ha^{-1}$)	Grain N (%)	Straw N (%)
0	1477c	2291d	3768d	0.86c	0.74c
45	3295b	3780c	7075c	0.92c	0.81b
90	5302a	6523b	11,825b	1.24b	0.89a
135	5470a	6783a	12,253a	1.33a	0.87a

Means followed by same letters are not significantly different.

record any significant increase in grain yield relative to 90 kg N ha^{-1} as shown in Table 5. Marked differences in grain yield were however observed between application of N at 135 $kg·ha^{-1}$ and 45 and 0 kg N ha^{-1} with a 1.6 and 3.7-fold increase respectively. Although there was no significant difference in grain yield between the 90 kg N ha^{-1} and 135 kg N ha^{-1} treatments, straw yield was significantly higher when 135 kg N ha^{-1} was applied relative to the 90 kg N ha^{-1}.

Straw N yield ranged from 0.74% for no nitrogen to 0.89% for 90 kg N ha^{-1}. Despite the difference in N rates, the N content of straw and grain from the fertilized fields varied over a narrow range with no difference in straw N between 90 and 135 kg N ha^{-1}.

Grain N for 135 kg N ha^{-1} was however, significantly higher than that of 90 kg N ha^{-1}. Table 6 shows the quantities of input used and the activities by farmers from the survey. The inorganic fertilizer NPK was the most applied input by farmers, ranging from 200 $kg·ha^{-1}$ to 450 $kg·ha^{-1}$.

Field preparation consumed between 18 and 25 $L·ha^{-1}$ of diesel, whereas between 50 and 75 L of diesel was used during harvesting. Pesticide use was between 2 and 6 $L·ha^{-1}$. The mean estimated carbon footprint from input use and major activities from survey data was 1520.1 kg CO_2-eq ha^{-1} yr^{-1} (Table 7). In terms of activities and input use, nitrogen fertilizer was the highest contributor, accounting for 41.6% of the carbon footprint. Transportation was the next highest contributor, accounting for 16.3% of the carbon footprint. Pesticide use, milling and field preparation were the lowest contributors, accounting for 6.3%, 5.4% and 4.0% respectively, to the carbon footprint.

Results of the carbon footprint (per hectare), carbon footprint (per kg grain yield), biological carbon and net carbon for different N rates from experiments conducted over 3 years are presented in Table 8.

The carbon footprint for the different nitrogen rates differed significantly ($p < 0.05$) in all cases with 135 kg N ha^{-1}, recording the highest carbon footprint of 1717 kg CO_2-eq ha^{-1}. This represents about 14% increase in the carbon footprint compared to applying 90 kg N ha^{-1}.

The carbon footprint increased such that as the nitrogen fertilizer rate increased, a positive correlation between nitrogen fertilizer rate and carbon footprint was observed (Figure 1). Compared to the control, the carbon footprints of 45, 90 and 135 kg N ha^{-1} increased by 22.0%, 41.9% and 49.8%, respectively.

Table 6. Inputs applied by farmers, grain yield and diesel used by machinery operators during survey.

Input/Activity	Minimum	Maximum	Average
a) Input	-------------------------------- kg·ha^{-1} ------------------------------------		
NPK	200	450	319
Urea	50	150	125
SA	100	150	125
Grain yield	3600	5200	4675
b) Diesel/Chemicals	------------------------------- L·ha^{-1} -------------------------------------		
Field preparation	18	25	23.6
Harvesting	50	75	65
Pesticides	2	6	3.4

SA = sulphate of ammonia.

Table 7. Carbon dioxide equivalent emission and contribution of major activities from the mean survey data.

Source	CH_4	N_2O	CO_2	C Footprint (kg CO_2-eq ha^{-1})	contribution %
	-------(kg CO_2-eq ha^{-1})-------				
Field preparation	2.85	0.122	58.1	61.1	4.0
Harvesting	7.85	0.335	170.4	178.6	11.7
Irrigation			224.0	224.0	14.7
Milling			81.6	81.6	5.4
Transportation	10.9	0.465	236.3	247.7	16.3
Fertilizer		595.8	37.1	632.9	41.6
Pesticides			94.2	94.2	6.3
TOTAL	21.6	596.2	901.7	1520.1	100.0

Table 8. Carbon footprint, biological carbon and net carbon for different N rates from experiment over 3 years.

N rate (kg·ha^{-1})	C footprint (kg CO_2-eq ha^{-1})	C footprint (kg CO_2-eq kg^{-1} grain)	Biological C (kg·ha^{-1})	Net Carbon (kg·ha^{-1})
0	862d	0.593b	916d	54c
45	1106c	0.342a	1512c	406b
90	1483b	0.280a	2609b	1126a
135	1717a	0.316a	2823a	1106a

Means followed by same letters are not significantly ($p < 0.05$) different.

The carbon footprint (on per kg grain basis) ranged from 0.280 kg CO_2-eq kg^{-1} grain for 90 kg N ha^{-1} to 0.593 kg CO_2-eq kg^{-1} grain for the control (0 kg N). On average, biological carbon (carbon fixed) ranged from 916 kg C ha^{-1} (for 0 kg

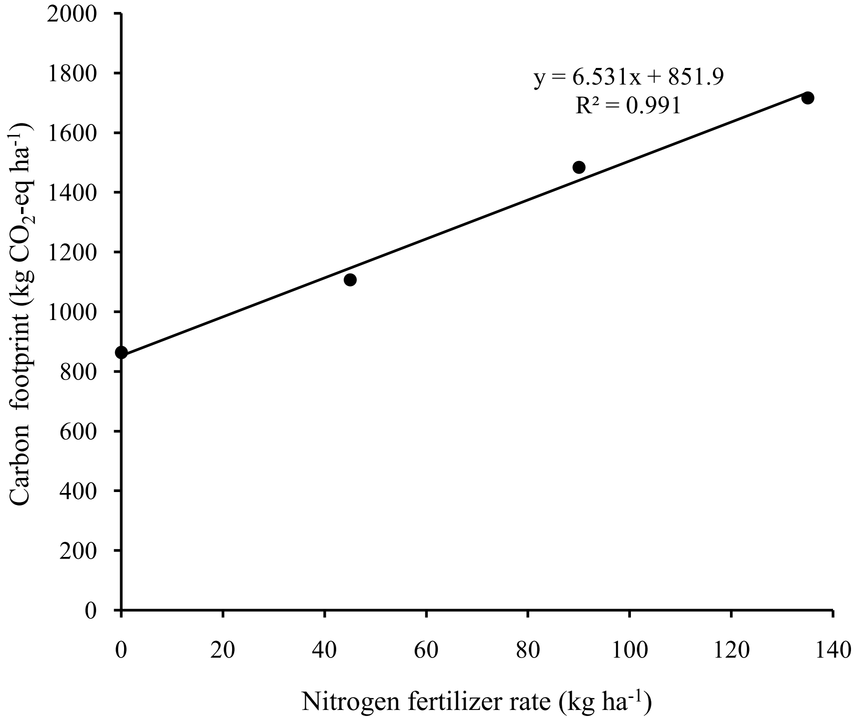

Figure 1. Relationship between carbon footprint per hectare and N fertilizer rate.

N ha^{-1}) to 2823 kg C ha^{-1} (for 135 kg N ha^{-1}). When nitrogen was applied at 90 kg N ha^{-1}, 2609 kg C ha^{-1} was biologically fixed. This represents a 285 and 1.72 fold increases over those of the 0 and 45 kg N ha^{-1} treatments respectively. On the contrary, the 2609 kg C ha^{-1} which was biologically fixed by the treatment that received 90 kg N ha^{-1}, was only about 92% of that fixed by the treatment at 135 kg N ha^{-1} as indicated in Table 8.

Net carbon, estimated as the difference between the carbon fixed biologically through photosynthesis and the carbon emitted from the use of inputs, was highest for 90 kg N ha^{-1}, although this was not different compared to 135 kg N ha^{-1}. Applying N at 0, 45, 90 and 135 kg N ha^{-1} provided net carbon of 52, 406, 1126 and 1106 kg C ha^{-1}, respectively.

4. Discussion

4.1. Biomass Yield and Nitrogen Content

Application of nitrogen fertilizer had a major effect on straw production. Straw yield was significantly higher in the treatment that received 135 kg N ha^{-1} than 90 kg N ha^{-1}. This is an indication that at a higher nitrogen application rate of 135 kg N ha^{-1}, there was more partitioning to vegetative plant parts relative to reproduction parts. Despite the difference in N rates, the N content of residues and grain from the fertilized fields varied over a narrow range with no difference in straw N between 90 and 135 kg N ha^{-1}. However, grain N for 135 kg N ha^{-1} was significantly higher than grain N at 90 kg N ha^{-1}. The findings from this study are in agreement with results from [32], who observed in a study on rice that above 120 kg N ha^{-1}, there was no significant increase in yield. [33] attributed such responses to soil available nitrogen. [32] again observed that differences in straw N between 90 and 120 kg N ha^{-1} were not significant and they attributed this to the higher grain yield and N content of grain at higher N rates. This means that at higher N rates, more N is immobilized to grain to increase the grain N content.

4.2. Greenhouse Gas Emission and Carbon Footprint

Although the carbon footprint in this study was about 3 times higher than that observed for northern Ghana by [12], both findings are in agreement in terms of the contribution of inorganic fertilizer application to the carbon footprint. According to [12], inorganic fertilizer accounted for 72% of the carbon footprint for rice in northern Ghana compared to 41.6% from the survey in this study. The significant positive correlation between N fertilizer rate and carbon footprint (**Figure 1**) indicates that nitrogen fertilizer had a major effect on greenhouse gas (GHG) emissions. [34] observed a significant positive correlation between N fertilizer rate and carbon footprint for rice. Although increasing the N fertilizer rate always resulted in a higher carbon footprint (on a per hectare basis), this was not always the case for carbon footprint (on per kg grain basis). This is mainly because of the increased yield relative to the carbon footprint due to the increase in N rate [35]. The carbon footprint (on per kg grain basis), which ranged between 0.280 and 0.593 kg CO_2-eq kg^{-1} grain, was relatively lower than the 0.80 kg CO_2-eq kg^{-1} grain that was observed for rice by [36] using an N rate of up to 300 kg·ha^{-1}. [37] and [38] also recorded carbon footprints of 1.36 and 1.06 kg CO_2-eq kg^{-1} grain, respectively, in China. The differences observed in the carbon footprint are probably due to the higher amounts of input and energy use. Due to the long periods required to observe major changes in soil carbon stocks, this study did not follow changes in soil carbon stocks because of the short duration of the study. However, it is expected that higher straw input from rice residue will add more carbon to the soil [39]. The higher biomass production observed at 135 kg N ha^{-1} (**Table 7**) is probably due to more carbon distribution to aboveground plant parts [40]. Increased N fertilizer rate, which resulted in increased biomass production (carbon biologically fixed), did not always result in the highest net carbon because, in some cases the high biomass production was offset by higher emissions. In this study, all the N rates assessed resulted in positive net carbon, indicating that the carbon biologically fixed was always higher than the carbon due to farm operations and input use. These findings differ from those of [41], who observed higher CO_2 emissions from rice production than was biologically fixed. On the contrary, [42] observed that rice paddy agroecosystems were significant net carbon sinks under optimal N fertilizer rates. [43] also observed that increased N fertilizer rates led to increased carbon sequestration in rice paddies. Such discrepancies could be a result of the levels of energy and input used and the rates of N applied in such studies. Optimized N rates may differ from region to region due to a host of other factors. Efforts should therefore be made to identify optimal N fertilizer rates and technologies that ensure profitability to farmers while also protecting the environment.

4.3. Optimizing Nitrogen Application for Rice Production and Emission Reduction

According to [44], nitrous oxide emissions from agricultural soils occur through nitrification and denitrification in soils, especially from organic and inorganic fertilizers. The emissions, however, are dependent on management practices, soil and climatic conditions and fertilizer types. With increasing demand for food due to rising population, acreage put under crop cultivation and the intensity of cropping systems will most likely continue to rise, leading to increased emissions. There is therefore the need for strategies that help reduce emissions whilst ensuring that crop yields are not compromised. Although some strategies, for instance, minimum or no tillage, fertilizer placement and timing of fertilizer application, are already in use, they are not necessarily targeted at emission reduction. Any option that would be attractive to farmers should be easy to apply and cost effective. Additionally, strategies that bring more benefits in terms of yield and reduction in GHG emissions would be more acceptable to environmentalists and farmers as well. Rice farmers may not be ready to adopt emission reduction strategies unless these strategies improve farmer profits. For example, information from this study showed that, although deep placement of urea in soil has more environmental and economic benefits, some farmers are unwilling to adopt urea deep placement because it is labour intensive. For many rice farmers to readily adopt deep placement of urea, technologies that make the application easier are required. According to [45], optimized N application rate for rice production should be such that it guarantees the high yields required by farmers while also protecting the environment. Results from this work showed that, although the N application rate of 135 kg N ha^{-1} did not significantly increase yield relative to 90 kg N ha^{-1}, it produced significantly higher amounts of biomass and higher carbon footprint. The significantly higher biomass production at 135 kg N ha^{-1} is due to the positive effect of increased N, which is likely to contribute more to soil carbon. It is worth noting that, although applying N at 90 $kg \cdot ha^{-1}$ resulted in lower biomass and carbon footprint compared to that of 135 $kg \cdot ha^{-1}$, the yields obtained as well as that of net carbon produced were similar as indicated in **Table 4** and **Table 7**, respectively. On the contrary, although a lower N fertilizer rate of 45 $kg \cdot ha^{-1}$ resulted in lower emissions, it did not guarantee relatively high yields. Applying N at 90 $kg \cdot ha^{-1}$ gave relatively high yield, produced relatively lower emissions and had relatively high positive net carbon. To the resource constrained local farmer, applying N at 90 $kg \cdot ha^{-1}$ makes economic sense due to the reduced cost of inputs without a significant reduction in yield. Therefore, applying N at 90 $kg \cdot ha^{-1}$ is recommended to ensure relatively high yields while reducing emissions. More research should focus on other management practices such as water management, timing of N application, etc. to ensure emission reduction while maintaining high yields.

5. Conclusion

Increasing the N application rate increased GHG emissions and carbon footprint in flooded rice cropping systems. Nitrogen fertilizer was the biggest contributor to GHG emissions in irrigated rice production, as observed in this study. Increasing the N fertilizer rate generally resulted in increased yield and biologically fixed carbon. All the N application rates assessed resulted in positive net carbon, perhaps due to the relatively lower N rates applied in this study. Between 862 and 1717 kg CO_2-eq ha^{-1} was emitted from rice fields per season. Applying N fertilizer at 90 kg·ha^{-1} maintained yields, reduced GHG emissions and achieved positive net carbon. This study confirms the recommended N fertilizer rate (90 - 100 kg N ha^{-1}) for irrigated rice farmers to be the best N rate to ensure relatively high yields while keeping emissions at reduced levels. More research should focus on other management practices such as water management and timing of N application to ensure emission reduction while giving or maintaining high yields.

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Conflicts of Interest

The authors declare no conflict of interest in this research.

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