Carbon footprint of maize planting under intensive subsistence cultivation in South Korea

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Abstract

Purpose – During the planting process, agricultural products produce large amounts of greenhouse gas (GHG) emissions. This has placed tremendous pressure on sustainable global development. Many countries and regions in the world have adopted intensive subsistence cultivation methods when planting maize; however, limited studies exist on these methods. The main purpose of this research is to show the impact of climate change on maize yields and carbon footprint (CF) in South Korea over 10 years, find the proper operating method and promote the advanced combination of inputs for the sustainable development of maize farmers.

Design/methodology/approach – This study used survey data from the South Korea Rural Development Administration of 2010, 2014 and 2019 to estimate the CF of maize planting under intensive subsistence cultivation. Life-cycle assessment was used to determine the CF. Farmers were grouped according to significant differences in yield and GHG emissions. Linear regression was used to measure the dependence of the main contributors on the CF production and carbon efficiency.

Findings – In South Korean maize planting, N in chemical fertiliser was the most significant contributor to the CF and organic fertiliser was the most significant input. The use of chemical and organic fertilisers

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significantly affects the production of the CF and carbon efficiency. Households in the high-yield and low-GHG emission groups are more sustainable because they generate the least GHG when producing and earning through maize cultivation. Globally, maize production in South Korea has a relatively low CF and maize production produces fewer GHG.

Originality/value – This study provides information for policymakers to determine key operational options for reducing GHG emissions using intensive subsistence cultivation of maize production in South Korea and other countries.

Keywords Carbon footprint, Maize planting, Intensive subsistence cultivation, Life cycle assessment, Greenhouse gas emissions, Sustainable development

Paper type Research paper

1. Introduction

The carbon footprint (CF) of agricultural fields is a measure of the total greenhouse gas (GHG) emissions during the life cycle of crops. Agricultural land accounts for 37% of the Earth's land surface, while agriculture produces 52% and 84% of global anthropogenic methane and nitrous oxide emissions, respectively [Food and Agriculture Organization of the United Nations (FAO, 2015)]. According to the Intergovernmental Panel on Climate Change (IPCC), GHG emissions from agriculture are responsible for up to 30% of anthropogenic emissions (IPCC, 2019). According to the latest figures from the Consultative Group on International Agricultural Research (CGIAR), the global food system is responsible for up to one-third of all human GHG emissions (Gilbert, 2012). Climate change caused by GHG emissions has seriously affected the survival and development of mankind.

Maize is one of the most important agricultural crops, ranking 11th in global food production (Wang *et al.*, 2015). Maize yield increases have been accomplished in part by increasing the use of agrochemicals, such as chemical fertilisers, pesticides and supplemental fieldwork operations (Owusu *et al.*, 2012; Foley *et al.*, 2011; Huysveld *et al.*, 2015) . However, contemporary agricultural methods have the potential for a wide range of negative environmental consequences (Brentrup *et al.*, 2004).

Large amounts of maize are planted in the Golden Maize Belt, which are mechanised planting areas with flat land. However, there are still many countries and regions in the world where maize is grown using subsistence-intensive cultivation methods, especially in some southern African countries (Alberts *et al.*, 2019).

Few scholars have used the national survey database to focus on the intensive subsistence cultivation of maize. South Korea is an example of an intensive subsistence maize-planting country, which can provide meaningful experience in increasing yields and reducing GHG emissions.

South Korea has long relied on food imports and is the world's second-largest importer of maize (Ranum *et al.*, 2014). There is high demand for maize in the domestic market. Climate change has reduced food production (Challinor *et al.*, 2014), which has affected South Korean maize households, further exacerbating the conflict between supply and demand. Maize households are facing a complex situation: it is necessary to increase production and simultaneously important to meet the low GHG emission requirements of sustainable development. Therefore, whether there is a method to meet both needs is a hot topic of academic concern.

Scholars have significantly contributed to the perspective on emission reduction (Boone *et al.*, 2016). Many researchers have used the life cycle assessment (LCA) method to focus on progressive crop production stages. Different field management methods can significantly impact GHG emissions (Gkisakis, 2020). For example, the GHG emissions of irrigated systems are 40% higher than those of rainfed systems (Zhang *et al.*, 2018). The carbon emissions from food production vary by country. Especially in developing countries such as China and Brazil, GHG emissions have increased significantly since 2010 (Li *et al.*, 2021; Nara *et al.*, 2021).

However, agricultural emissions have declined in developed countries (Bajan and Mrówczyńska-Kamińska, 2020). Bio-farming has shown the potential to reduce GHG emissions (Eranki *et al.*, 2019) and different operation systems also contribute to different GHG emissions. Qi *et al.* (2018) compared four types of cultivation patterns: the traditional pattern, optimal pattern, super-high-yield pattern and high-yield and high-efficiency patterns. The GHG emissions results were different, with fertilisers accounting for over 65% of the emissions in each pattern. It was found that the super-high-yield pattern had both a higher yield and lower CF.

The LCA method can ensure the comparability of research samples, which can reduce biases arising from a diversity of field management measures. In some forms of agricultural production, such as greenhouse vegetable production, the short lifecycle and fixed area provide a robust estimation of GHG emissions. Compared to conventional systems of vegetable production, an intercropping system is characterised by a greater efficiency of land use and inputs, with GHG emissions in intercropping configurations (16,368 $kg\ CO_2\ eq\ ha^{-1}$) reported to be approximately 35% lower than the total emissions in monoculture systems (25,273 $kg\ CO_2\ eq\ ha^{-1}$) (Pereira *et al.*, 2021). So *et al.* (2010) used a database of different types of peppers to analyse carbon emissions and found that different species of the same type of vegetable can exhibit different GHG emissions.

To achieve sustainable production, considering the input of planting, the use of fertilisers provides the necessary nutrients for crop growth. Organic fertilisers, as an alternative to chemical fertilisers, combat the pollution problem and can be used to increase crop production (Baweja *et al.*, 2019). Regular additions of organic materials, such as animal manure, crop residues and municipal wastes, are critical for sustaining agricultural soil tilth fertility and productivity (Jamil, 2006). Organic matter in algae, manure and sewage sludge has been proven to provide nutrients for crops and has the potential to aid in the development of sustainable agriculture (Aiysha and Latif, 2019). The meaning of sustainable agriculture is complex; it includes, but is not limited to, organic, alternative, regenerative ecological and low input. It also requires that the products produced must be of high quality, protect their resources and be both environmentally safe and profitable (Laurett *et al.*, 2021).

The main purpose of this study was to calculate the CF of maize planting in South Korea; thus, all resource inputs to maize planting were included and the survey data reported the inputs per unit area [1]. A database spanning a decade shows the impact of climate change on maize yields and the CF in South Korea and samples from across the country ensure that the study is representative. The main aim is to provide policymakers with information to determine key operational options for reducing GHG emissions in South Korean maize production.

2. Materials and methods

2.1 Study area

South Korea lies between latitudes 33° and 39°N and longitudes 124° and 130°E, tends to have a humid continental climate and a humid subtropical climate and is affected by the East Asian monsoon. Flat arable agricultural land is a scarce resource in South Korea. An agricultural land area per capita of less than 0.1 ha is considered extremely small (Waceke and Kimenju, 2007). In South Korea, this number is 0.03 ha.

Figure 1 shows the maize-planting period in South Korea. There are three stages: sowing, cob formation and harvesting. Under normal climatic conditions, the maize planting period in South Korea is more than 78 days and less than 109 days. Farmers may start maize sowing at different times. To harvest before October, farmers should sow as early as 10 April and not later than 8 July. The later the sowing, the shorter the maize growing time and the lower the quality of maize (Baum *et al.*, 2019). Before sowing, the base fertiliser should be applied, which is mainly organic fertiliser with manure as the main component (Baum *et al.*, 2019). According to the Maize Research Institute of South Korea, the recommended doses for using manure fertiliser are 1,500 kg per 1,000 m^2; for nitrogen (N) fertilizer, 16 kg per 1,000 m^2; for phosphorus (P) fertiliser, 15 kg per 1,000 m^2; and for potassium (K) fertiliser, 10 kg per 1,000 m^2. In the process of planting, second and third fertilisations should be used. Typically, the second fertilisation is between sowing and cob formation, mainly using urea fertiliser, with a recommended dose of 16 kg per 1000 m^2. The third fertilisation could be earlier or later than cob formation, mainly using urea fertiliser, with recommended doses of 16 kg per 1000 m^2, or it can be divided into two doses (each time, 8 kg per 1000 m^2).

2.2 Data collection

This research on South Korean maize-planting households was based on rural household sample survey data from 2010 (87 households), 2014 (86 households) and 2019 (116 households) collected by the South Korea Rural Development Administration. The provincial distribution over three years in South Korea is shown in Figures S1, S2 and S3. The main purpose of this survey was to make agricultural development more efficient and sustainable in South Korea (South Korea Rural Development Administration, 2020). This study used a portion of the maize survey data. Based on the 2010 South Korean Agricultural Census data, the number of samples was determined by considering relative standard errors and target errors and the number of samples was allocated by province by reflecting the population cultivation ratio. Based on the probability proportional extraction proportional to

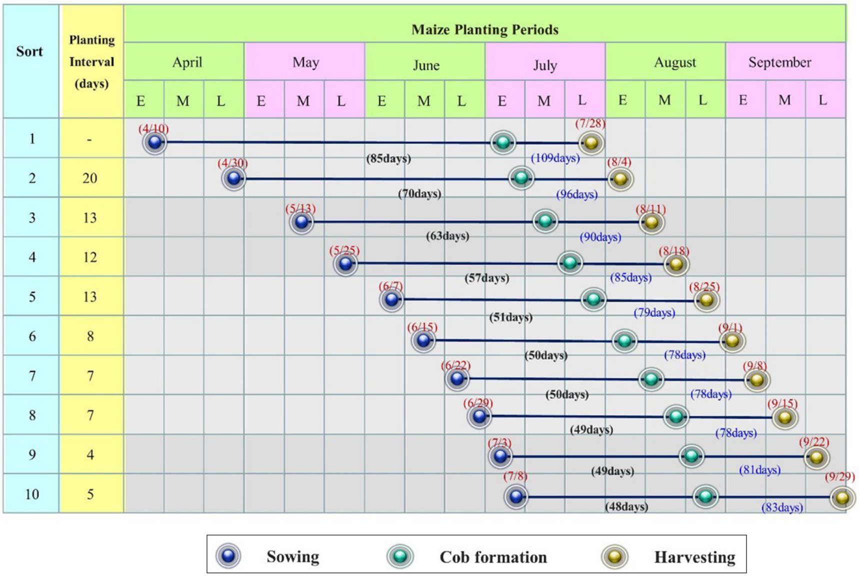


Figure 1.
Maize planting periods in South Korea

the cultivation area of the survey crops in the province, the survey city and county were selected and the number of samples was distributed. The selected city and county agricultural technology centres selected sample farms in parallel with the double extraction and allocation methods. A sample farm was replaced by a similar farm of the same size in the relevant area within the scope to ensure that the representativeness does not decrease only when the survey is impossible because of the conversion of crops, full-time business, closure or director of the sample farm. This ensured that the results from the sample reflected the maize planting status of the entire country.

2.3 Methods

2.3.1 Carbon footprint and life cycle analysis. The CF is a measure of the total amount of GHG emissions, directly or indirectly caused by an activity (Wiedmann and Minx, 2008). LCA is a method for evaluating the impact of a product system on the environment at all stages of its lifecycle (Fawer and Hutchison, 1997). It is included in the ISO14000 family of standards for environmental management systems, which is widely used to evaluate the sustainability of crops and is now increasingly applied to the environmental impact assessment of agricultural crops (Eranki *et al.*, 2019). The CF is part of the LCA of a crop and is widely calculated in terms of GHG emissions (Al-Ansari *et al.*, 2015). In this study, global warming potential (GWP-100-year time horizon) was used to define total GHG emissions. This includes CO_2, N_2O and CH_4, but maize is usually planted in drylands; thus, the CH_4 emissions are negligible (He *et al.*, 2019).

The LCA method includes the following:

- The system boundaries were set. This study calculated the GHG emissions estimated individually over all crop production stages (cradle-to-farm gate) according to de Figueiredo *et al.* (2017), Ntinas *et al.* (2017) and Pereira *et al.* (2021).
- Collecting life cycle inventory.
- Aggregating environmental impacts based on characterisation factors (Eranki *et al.*, 2019).

Details of the LCA method follow.

2.3.2 Systems boundary and functional unit. In the LCA method, the maize CF (cradle-to-farm gate) is mainly determined by inputs during planting. The emissions were classified into three input-related categories:

(1) Upstream input manufacturing and transport. In this category, seeds, fertilisers (chemical and organic), insecticides, sterilisers, herbicides and films were evaluated.

(2) GHG emissions during the maize cultivation process. In this stage, tractors were used for maize cultivation operations, which consume diesel and gasoline and electricity is consumed in the irrigation process; the main GHG produced at this stage is CO_2. Meanwhile, N_2O is produced during composting of urea and manure.

(3) Carbon sequestration. In some studies, dry land crop carbon sequestration was mainly generated from soil carbon fixation during composting, crop residues left in the soil and carbon sequestration from no-till management (Dachraoui and Sombrero, 2020; Eranki *et al.*, 2019; Zhang *et al.*, 2017). In the surveyed area, maize stalks were removed from the land after harvest and farmers did not use no-till management in their soil land. Therefore, only carbon sequestration from the manure compost was considered in this study (Figure 2).

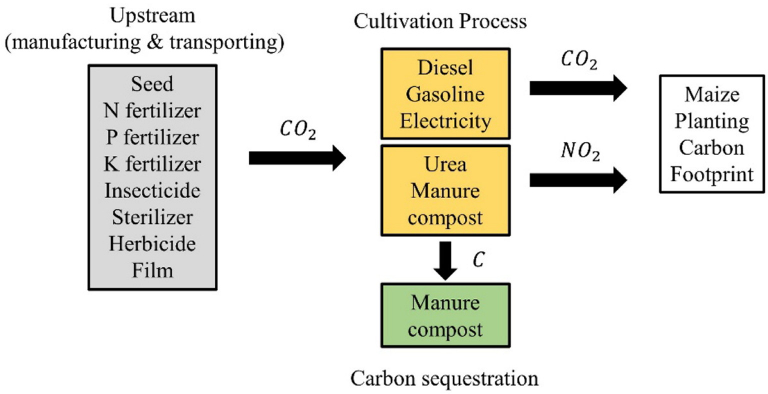


Figure 2. Cradle-to-farm gate maize planting carbon footprint system boundary

Notes: The grey box indicates CO_2 emissions from agricultural input manufacturing and transporting; golden boxes indicate CO_2 and NO_2 emissions from maize cultivation process; the green box indicates the carbon sequestration from the manure compost

The CF is defined as the sum of all direct and indirect GHG emissions and sequestration in the production progress, expressed in carbon dioxide equivalents (CO_2eq), based on the LCA approach according to ISO (2018) 14067 principles. Many scholarly studies have followed these principles (Chen *et al.*, 2020; Eranki *et al.*, 2019; Hou *et al.*, 2021). Using the IPCC method (Penman *et al.*, 2006), the total emissions of maize planting were calculated in terms of their CO_2eq. The CF of maize planting was assessed by calculating net total GHG emissions. The global warming potential of CO_2 is equal to 1 and the nitrous oxide (N_2O) potential is 298 over a period of 100 years (Penman *et al.*, 2006).

Over the cradle-to-farm gate maize planting life cycle, the CF was estimated as both CO_2 and N_2O emissions. The total GHG emissions were determined from the different input factors and, thus, the CF calculation method is expressed as follows:

$$GE = UG + PG \tag{1}$$

where GE is the total GHG emissions in $kg\ CO_2\ eq\ ha^{-1}$ and UG is the GHG emissions from upstream, which includes GHG emissions from the manufacturing and transportation of inputs. PG is the GHG emissions from the maize cultivation process:

$$UG = \sum_{i=1}^{n} UI_i \times EF_i \tag{2}$$

where UI_i represents the upstream manufacturing and transportation of the i_{th} input and EF_i is the CO_2 emission factor of the i_{th} input:

$$PG = \sum_{i=1}^{n} PI_i \times EF_i + \sum_{i=1}^{n} F_N \times \delta_N \times \frac{44}{28} \times 298 \tag{3}$$

where PI_i is the i_{th} input during maize cultivation and the unit of N, P and K fertilisers (whether chemical or organic), pesticides, gasoline, diesel and film is kg. The unit of electricity used for irrigation is kWh. EF_i is the carbon dioxide emission conversion coefficient for each factor and F_N is the quantity of N fertiliser (N in chemical and organic fertilisers) (kg). δ_N is the emission factor for N_2O emissions caused by N fertiliser. $\frac{44}{28}$ is the molecular weight of N_2 relative to N_2O. 298 is the global warming potential of N_2O over a 100-year period (Penman *et al.*, 2006):

$$CS = M_C \times 10\% \times \frac{44}{12} \tag{4}$$

where CS is the carbon sequestration during maize cultivation in kg CO_2 eq ha^{-1}. M_C represents total carbon input during manure compost in kg C ha^{-1}. 10% is the proportion of carbon in manure compost fixed in soil (Shin *et al.*, 2017). $\frac{44}{12}$ is the molecular conversion factor of C to CO_2:

$$NGE = UG + PG - CS \tag{5}$$

where NGE represents the CF during maize planting in kg CO_2 eq ha^{-1} and is the net GHG emission.

The emission inputs and conversion factors are listed in Table 1.

The GHG emissions of all the inputs were assessed and time dynamic changes were observed in the CF using two functional units: CF production (CFY), expressed in units of kg CO_2 eq kg^{-1} and the income CF [carbon efficiency (CFI)]. CF per unit of income was defined as carbon efficiency, expressed in units of kg CO_2 eq 10^4 won^{-1}. It is calculated using the following two equations:

$$CFY = \frac{NGE}{A} \tag{6}$$

Emission input	Emission or scaling factor	Reference
Upstream manufacturing and transporting (CO_2)		
Maize seed	3.85 kg CO_2 eq kg^{-1}	West and Marland (2002)
N fertiliser	6.38 kg CO_2 eq kg^{-1}	West and Marland (2002)
P fertiliser	0.61 kg CO_2 eq kg^{-1}	West and Marland (2002)
K fertiliser	0.44 kg CO_2 eq kg^{-1}	West and Marland (2002)
Insecticide	18.10 kg CO_2 eq kg^{-1}	West and Marland (2002)
Herbicide	19 kg CO_2 eq kg^{-1}	West and Marland (2002)
Steriliser	17.2 kg CO_2 eq kg^{-1}	West and Marland (2002)
Film	2.50 kg CO_2 eq kg^{-1}	Penman *et al.* (2006)
Cultivation process (CO_2, N_2O)		
Diesel	3.45 kg CO_2 eq kg^{-1}	Lal (2004)
Gasoline	3.12 kg CO_2 eq kg^{-1}	Lal (2004)
Electricity	0.92 kg CO_2 eq kg^{-1}	Penman *et al.* (2006)
N fertiliser	1.20%	Shin *et al.* (2017)
Manure compost	0.60%	Shin *et al.* (2017)
Carbon sequestration (C)		
Manure compost	3.43%	Shin *et al.* (2017)

Table 1. Emission inputs and scaling factors considered in the calculation of GHG emissions for maize planting

$$CFI = \frac{NGE}{I} \quad (7)$$

where CFY is the CF production of all inputs in a 1 ha planting area and A is the maize yield in $kg\ ha^{-1}$. CFI is the carbon efficiency of all inputs in a 1 ha planting area and I is the income of maize-planting households at 10^4 $won\ ha^{-1}$.

2.3.3 Fertiliser emissions and carbon sequestration. The surveyed households used chemical and organic fertilisers. The chemical fertilisers were mainly urea and compound fertilisers and the organic fertilisers were mainly animal manure. For the estimation of GHG emissions from fertilisers, the pure N, P and K content of the fertilisers was calculated.

Organic fertilisers combined with manure compost can provide nutrients to maize. The amount of manure compost in the organic fertiliser, as well as the quantities of N, P_2O_5 and K_2O in the manure compost, was estimated using the conversion coefficients indicated in Table 2 and comparable work by Shin *et al.* (2017). The conversion coefficients used were the average values for pig manure compost and cow manure compost. The maize planting in Shin *et al.*'s (2017) study was led by the South Korean Rural Development Administration's approved approach and the maize and soil types were the same as in the current study. This study also examined the emission conversion and scaling factors of manure compost during maize growth as well as carbon sequestration (Table 1). The following equations describe the N, P_2O_5 and K_2O contained in the organic fertiliser:

$$PI_{OFN} = OF \times OM \times Z_N \quad (8)$$

$$PI_{OFP} = OF \times OM \times Z_P \quad (9)$$

$$PI_{OFK} = OF \times OM \times Z_K \quad (10)$$

where PI is the N, P_2O_5 and K_2O of organic fertiliser input; OF is the total amount of organic fertiliser; OM is the conversion coefficient of manure compost in organic fertiliser; and Z is the conversion coefficient of N, P_2O_5 and K_2O in manure compost.

2.3.4 Upstream emissions – seeds manufacturing and transporting. This study included indirect GHG emissions from maize seeds. In maize seed manufacturing and transportation, the main contribution of GHG is a consequence of the fuel used by farm machines and the energy consumed in the manufacturing, transportation and repair of machines. The emission factors of the maize seeds are shown in Table 1.

2.3.5 Upstream emissions – pesticides manufacturing and transportation. In the surveyed area, most farmers used three types of pesticides: insecticides, herbicides and sterilisers. In 2010, none of the farmers used sterilisers. The unit used in the survey was mL, and as done by West and Marland (2002), the volume unit was converted into a weight unit. The conversion coefficient was 1 and the GHG emissions of pesticides (insecticides,

Table 2.
N, P, K in organic matter

NPK in organic matter	Organic matter g/kg	*N* (%)	P_2O_5 (%)	K_2O (%)
Pig manure	29.48	1.55	2.72	1.04
Cow manure	31.18	1.42	2.61	0.83
Average	30.33	1.48	2.66	0.93

herbicides and sterilisers, individually) were calculated as indirect emissions from their manufacturing and transportation.

2.3.6 Upstream emissions – film manufacturing and transportation. For the films, the indirect emissions from plastic film manufacturing and transportation were calculated. Plastic films were widely used for maize planting in the surveyed area. The unit used in the survey was "m" and Penman *et al.*'s (2006) emission factor was used to convert the length unit into weight unit *kg*. The commonly used film in the survey area is 0.2 mm thick and 900 mm wide, making a 1-m length of film equivalent to 0.014285 kg.

2.3.7 Cultivation process emissions. Cultivation process emissions include the use of diesel, gasoline, electricity and the application of urea and manure compost in the maize planting process. For diesel and gasoline, the estimated GHG emissions were from a tractor using fuel. The unit used in the survey was "L" and as done in a study by Lal's (2004), the volume unit was converted into weight unit kg. The conversion coefficients of diesel and gasoline are 0.84 and 0.72, respectively.

For electricity, the energy use of the irrigation system in the surveyed area was measured; the unit of electricity was *kWh*.

For urea and manure compost, which are the main sources of N_2O emissions, the cultivation guidelines of South Korea Rural Development Administration were followed. During the maize cultivation process, the urea and manure compost were applied in sowing and cob formation (Figure 1).

2.4 Households grouping

To clarify the differences between farmers under different operating conditions, methods similar to those of Wang *et al.* (2018) and Chen *et al.* (2020) were used. The 289 household survey samples collected in 2010, 2014 and 2019 were divided into four groups based on average yields and GHG emissions: the high yield and high GHG emission group (HH), high yield and low GHG emission group (HL), low yield and high GHG emission group (LH) and low yield and low GHG emission group (LL).

2.5 Data processing and statistical analysis

Microsoft Office Excel 2016 was used to collect and manage the raw data, perform unit conversions and calculate the CF for maize planting and household grouping. Statistical analyses were conducted using SPSS 24 software. One-way ANOVA and least significant difference tests were used to detect significant differences between years and household groups. Statistical significance was set at $p < 0.05$ and the differences are indicated with the letters a, b and c. Linear regressions were performed to analyse the dependence of CFA and CFI on the increase in main contributors and the significance was set at $p < 0.01$.

3. Results

3.1 Yield, carbon footprint and profit of maize planting in South Korea

The yield, total GHG emissions, carbon sequestration, CF, production CF, carbon efficiency and profit of maize planting in 2010, 2014 and 2019 are summarised in Table 3. Among these, carbon efficiency dropped significantly from 2010 to 2019. The profits of maize farmers increased by 65% between 2010 and 2014 and then dropped by 102% between 2014 and 2019. The remaining statistical factors did not show significant differences between 2010 and 2019.

The income, cost and profit of maize households with significant differences in operating conditions over the past three periods were analysed. The results showed that the income of maize households in South Korea increased significantly from 2010 to 2014 and from 2014 to

2019. In terms of costs, the increase from 2010 to 2014 was not significant, but the increase from 2014 to 2019 was statistically significant. In terms of profit, there was no significant growth from 2010 to 2014, but there was a significant decline from 2014 to 2019 (Figure 3).

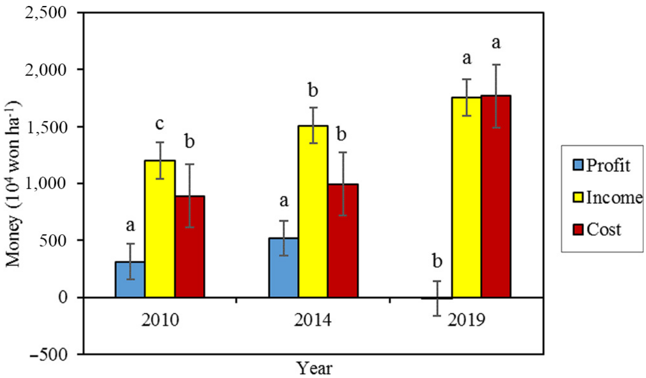
3.2 Different yields and greenhouse gas emissions in groups

To better analyse the specific differences between maize-planting households under different operating conditions, the 289 farmers surveyed over three years were divided into four groups and the above grouping method was used to analyse their CF and differences between groups. Figure 4 shows the distribution of yields and GHG emissions for all the surveyed households. All households were divided into four groups by average, with 48 farmers in the HH (17%), 78 farmers in the HL (27%), 56 farmers in the LH (19%) and 107 farmers in the LL (37%) groups. All four groups passed the significance test for yield and GHG emissions ($p < 0.05$) (Figure 5). The average yields of the four groups were 44,131 (HH),

Table 3. Descriptive statistics of yield, total GHG emissions (total GHG), carbon sequestration (CS), carbon footprint (CF), production carbon footprint (CFY), carbon efficiency (CFI) and profit in 2010, 2014 and 2019

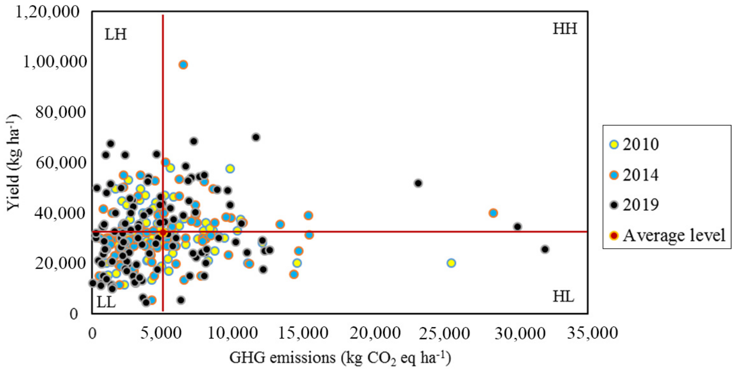
Year	Factors	Yield	Total GHG	CS	CF	CFY	CFI	Profit
2010	Average (87)	32,021.26	4,887.35	286.64	4,600.71	0.16	4.13a	312.98a
	SD	9,378.63	3,552.02	601.25	3,085.33	0.14	3.29	401.89
	SE	1,005.49	380.82	64.46	330.78	0.02	0.35	43.09
2014	Average (86)	32,499.33	5,341.21	246.56	5,094.65	0.18	3.85a	516.45a
	SD	13,023.65	4,296.39	375.63	4,129.34	0.16	3.15	619.36
	SE	1,404.38	463.29	40.51	445.28	0.02	0.34	66.79
2019	Average (116)	32,041.02	4,867.12	198.91	4,668.21	0.18	2.91b	−11.33b
	SD	14,835.18	4,979.64	599.17	4,599.64	0.19	2.80	850.39
	SE	1,377.41	462.35	55.63	427.07	0.02	0.26	78.96
Total	Average (289)	32,171.45	5,014.29	239.50	4,774.79	0.17	3.56	243.36
	SD	12,816.06	4,377.50	542.49	4,045.66	0.17	3.09	707.16
	SE	753.89	257.50	31.91	237.98	0.01	0.18	41.60

Notes: The numbers in parentheses indicate the sample sizes of surveyed households in 2010, 2014 and 2019. SD indicates standard deviation. SE indicates standard error. The different letters (a and b) behind the numbers indicate that there is a statistically significant difference ($p < 0.05$) in different years



Note: The error bars in the figure indicates the standard deviation

Figure 3. Differences among three years in economics situation



Notes: The yellow point in the figure indicates the yield and GHG emissions data of maize planting household in 2010, the green point indicates the data in 2014 and the black point indicates the data in 2019. The red point is the average value of GHG emissions and yield. To analyze the effect of different types of households on carbon footprint, the red lines divided the households into four groups: high yield and high GHG emissions group (HH), high yield and low GHG emissions group (HL), low yield and high GHG emission group (LH), low yield and low GHG emission group (LL)

Figure 4. Households in different groups

42,584 (HL), 24,647 (LH) and 23,154 (LL) $kg\ ha^{-1}$, respectively. The average GHG emissions of the four groups were 9,233 (HH), 3,209 (HL), 8,970 (LH) and 2,368 (LL) $kg\ CO_2\ eq\ ha^{-1}$, respectively.

3.3 Different contributors in the four groups

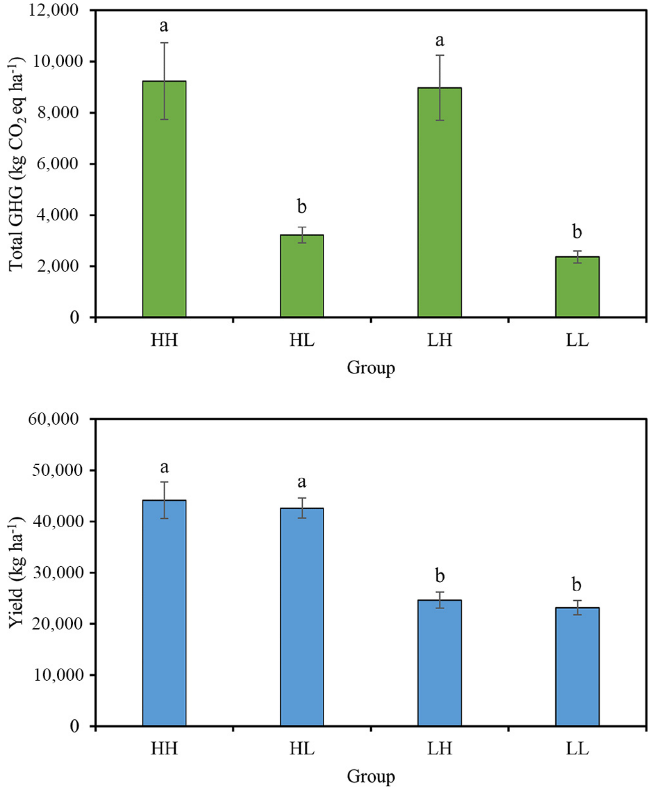
When measuring GHG emissions upstream, the HH group was significantly larger than the LH group, the LH group was significantly larger than the HL and LL groups and the largest contributor to carbon emissions upstream in the different groups was N in the chemical fertiliser, accounting for 51% (HH), 62% (LH), 50% (HL) and 51% (LL), respectively (Figure 6).

As shown in Table S1, except for insecticides and herbicides, the GHG emissions of all inputs differed significantly among the four groups. Specifically, the seed GHG emissions of the HH, HL and LL groups were significantly higher than that of the LH group. The GHG emissions of N, P_2O_5 and K_2O (in chemical and organic fertilisers) in the HH and LH groups were significantly higher than those in the HL and LH groups. The GHG emissions of sterilisers in the LH group were significantly higher than those in the other three groups. Diesel GHG emissions in the LL group were significantly lower than those in the other three groups and gasoline GHG emissions in the HH and HL groups were significantly greater than those in the LH and LL groups.

As shown in Figure 7, there were significant differences between the four groups in terms of GHG emissions during the planting process and carbon sequestration. The LH group had the largest share of GHG emissions during the planting process in the CF at 50% and the largest carbon sequestration volume at 543.77 $kg\ CO_2\ eq\ ha^{-1}$. The detailed data are listed in Table S1.

3.4 Income, cost, profit and carbon efficiency in different groups

Figure 8 shows the operating conditions and carbon efficiencies of the four groups. Overall, the HL group exhibited the most favourable operating conditions, the highest profit and the



Note: The error bars in the figure indicate the standard deviation

Figure 5.
Differences of total GHG emissions and yield among four groups

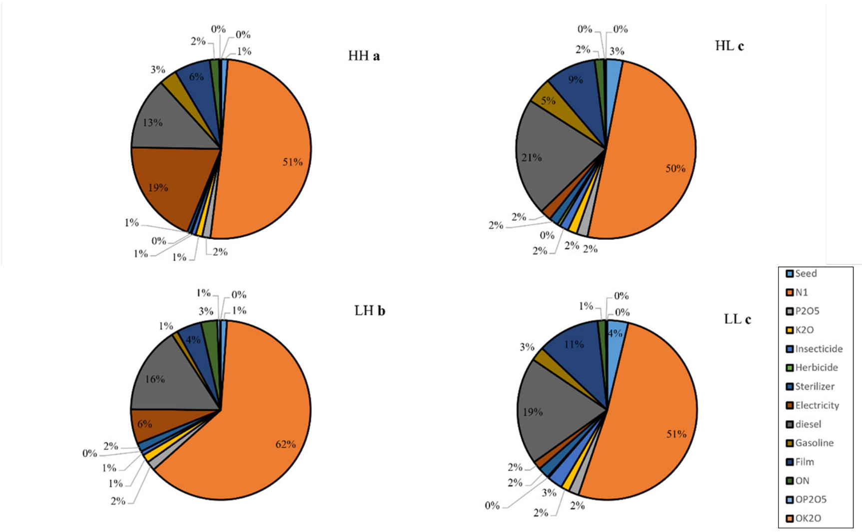
lowest CF, whereas the LH group had the worst operating conditions, the lowest profit and the highest CF. In terms of profit, that of the HL group was 219% higher than that of the LH group and that of the LH group was 273% higher than that of the HL group. The HH group had the highest income and cost at 64% and 71% higher than those of the lowest LL group, respectively.

4. Discussions

4.1 Greenhouse gas emissions, carbon footprint and yield in different countries

Based on time dynamic analysis, the changes in GHG emissions, CF and yield of South Korean maize households in 2010, 2014 and 2019 were stable at 5,014.29 (±147.17) $kg\ CO_2\ eq\ ha^{-1}$ 4,774.79 (±174.08) $kg\ CO_2\ eq\ ha^{-1}$ and 3,2171.45 (±150.19) $kg\ ha^{-1}$, respectively. However, the operating status (income, cost and profit) has undergone significant changes. Over time, income and costs have increased significantly; however, costs have had higher increases. This directly led to an average profit of $-11.33\ 10^4\ won\ ha^{-1}$ for South Korean maize households by 2019, that is, an overall loss in the maize planting operation.

China and the USA are the primary maize producers worldwide (Hou, 2021). In this study, the CF of maize production in China and the USA is provided in Table 4. China has a large land area, and maize cultivation differs between regions. In some areas of central



Notes: N1, P_2O_5 and K_2O indicate the N, P_2O_5 and K_2O, respectively, in chemical fertiliser; ON, OP_2O_5 and OK_2O indicate the N, P_2O_5 and K2O, respectively, in organic fertiliser. The different letters (a, b and c) behind the abbreviations (HH, HL, LH, LL) indicate that there is a statistically significant difference ($p < 0.05$) in different groups

Figure 6. Contribution of different input sources to the upstream GHG emissions in four different groups

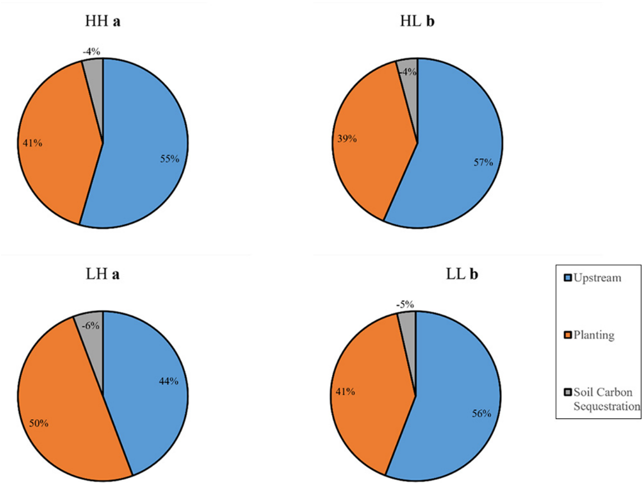


Figure 7. Contribution of upstream GHG emissions, planting process GHG emissions and soil carbon sequestration to the net GHG emissions (carbon footprint) in four different groups

China, the CF of traditional maize planting is 3,225.2 $kg\ CO_2\ eq\ ha^{-1}$, the yield is 6,719 $kg\ ha^{-1}$ and the CFA is 0.48 $kg\ CO_2\ eq\ kg^{-1}$ (Qi *et al.*, 2018). Yan *et al.* (2015) estimated the average CF of maize planting in the research area as 3,300 $kg\ CO_2\ eq\ ha^{-1}$, the yield as 7,000 $kg\ ha^{-1}$ and the CFA as 0.47 $kg\ CO_2\ eq\ kg^{-1}$. In the USA, according to a study by

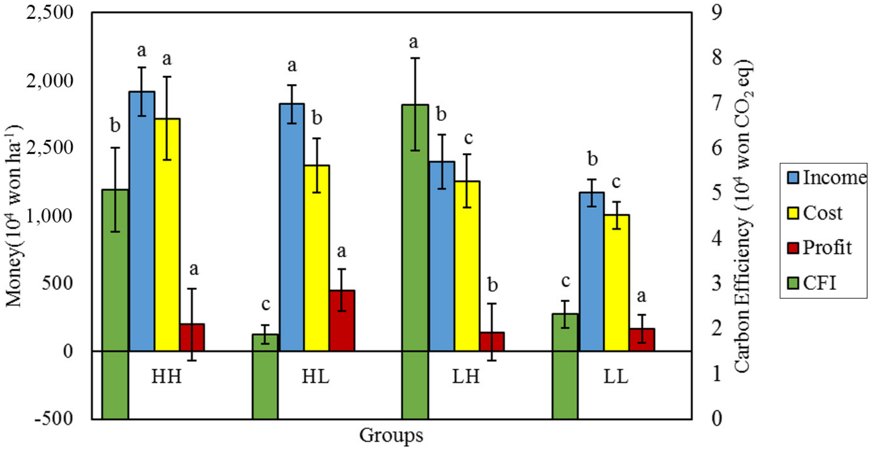


Figure 8.
Differences among four groups in income, cost, profit and carbon efficiency (CFI)

Table 4.
CF, yield and CFA in China, the USA and South Korea

Countries	CF	Unit	Yield	Unit	CFA	Unit	References
China	3,225	$kg\ CO_2\ eq\ ha^{-1}$	6,719	$kg\ ha^{-1}$	0.48	$kg\ CO_2\ eq\ ha^{-1}$	Qi *et al.* (2018)
China	3,300	$kg\ CO_2\ eq\ ha^{-1}$	7,000	$kg\ ha^{-1}$	0.47	$kg\ CO_2\ eq\ ha^{-1}$	Yan *et al.* (2015)
USA	21,450	$kg\ CO_2\ eq\ ha^{-1}$	85,800	$kg\ ha^{-1}$	0.25	$kg\ CO_2\ eq\ ha^{-1}$	Adom *et al.* (2012)
USA	13,250	$kg\ CO_2\ eq\ ha^{-1}$	53,000	$kg\ ha^{-1}$	0.25	$kg\ CO_2\ eq\ ha^{-1}$	Snyder *et al.* (2009)
South Korea	4,775	$kg\ CO_2\ eq\ ha^{-1}$	32,171	$kg\ ha^{-1}$	0.17	$kg\ CO_2\ eq\ ha^{-1}$	This research

Adom *et al.* (2012), the maize planting CF was estimated as 21,450 $kg\ CO_2\ eq\ ha^{-1}$, the yield as 85,800 $kg\ ha^{-1}$ and the CFA as 0.25 $kg\ CO_2\ eq\ kg^{-1}$. In a study by Snyder *et al.* (2009), the CF of maize planting was estimated as 13,250 $kg\ CO_2\ eq\ ha^{-1}$, the yield as 53,000 $kg\ ha^{-1}$ and the CFA as 0.25 $kg\ CO_2\ eq\ kg^{-1}$. In this study, the average CF was estimated as 4,775 $kg\ CO_2\ eq\ ha^{-1}$, the yield as 32,171 $kg\ ha^{-1}$ and the CFA as 0.17 $kg\ CO_2\ eq\ kg^{-1}$. This was mainly because of different cultivation conditions. The available land resources, mechanisation levels and climatic conditions for maize cultivation in China and the USA are better than those in South Korea. In addition, maize varieties grown in South Korea differ from those in China and the USA. Maize varieties (wax maize or sweet maize) grown in South Korea are primarily used for consumer consumption. Maize grown in China and the USA is mainly used in animal feed and industry (Wang *et al.*, 2015; Eranki *et al.*, 2019).

4.2 Main contributors

In intensive subsistence cultivation of maize, as in other studies under different cultivation conditions, the main contributor (average 54%) of the CF was N use in chemical fertilisers. In other studies, Yan *et al.* (2015) found that the contribution rate of N fertiliser was 74.6% and Jiang *et al.* (2020) found a contribution of 40% to 49.3%, while the contribution Huang *et al.* (2019) found ranged from 37.4% to 73.2%. The reasons for the different estimated contributions are as follows. First, the system boundary used in the CF calculation is different. Some studies calculated the entire CF of the maize industry, including the upstream and downstream parts of maize production. Thus, the components of the CF are different, leading to different contribution rates. Thus, the components of the CF accounting methods differ. In most areas, especially China and the USA, plastic films are not used in maize planting and are therefore not included in the CF. In some studies, pesticides, herbicides and sterilisers were not distinguished and the GHG emissions of pesticides were directly calculated. Finally, different cultivation scenarios were used. In maize CF studies of China and the USA, the contribution of pure N fertiliser was higher than that in this study (Adewale *et al.*, 2019; Qi *et al.*, 2018; Zhang *et al.*, 2018). In Africa, the contribution of N is often lower than that used in this study. China and the USA have vast land areas. Large amounts of maize are planted in the Golden Maize Belt, which has flat land. A significant amount of mechanical maize is planted. The diversity of inputs per unit area was lower than in this study and the use of N fertiliser was more common than in South Korea. In Africa, some of the studied cultivation conditions were similar to those of intensive subsistence cultivation. Under similar cultivation conditions, the African N fertiliser contribution was higher than that in this study; however, organic fertiliser was not used (Waceke and Kimenju, 2007).

Organic fertilisers are rarely used in maize production in China, the USA or Africa. This is partly because of the short production cycle of maize, which takes only four months from sowing to harvest. The use of mechanised planting in China and the USA is not conducive to the use of organic fertilisers. In Africa, there are few field management methods for maize cultivation and the high cost of commercial organic fertilisers increases production costs. However, the use of organic fertilisers effectively reduces the need for chemical fertilisers, thereby reducing the CF. Some studies indicate that intensive cultivation has low sustainability (Qi *et al.*, 2018) and the use of organic fertilisers is ignored in considering future intensive subsistence cultivation scenarios. This study defines the use of organic fertilisers as a characteristic of intensive subsistence cultivation. In the study area, organic fertiliser was the most important input, with a contribution rate of 91%, whereas its contribution to the CF was only 2.3%. This shows that under intensive subsistence cultivation of maize, the large-scale use of organic fertilisers is the main difference from other cultivation options. Therefore, with limited land resources, the use of organic fertilisers not only meets the growth needs of crops but also reduces GHG emissions.

As mentioned previously, the N in fertilisers is the main source of CF and has a significant positive impact on CFY and CFI (Figures 9 and 10). This means that as the amount of N used increases, farmers' yield CF and carbon efficiency increase. In terms of grouping, the N use of the high GHG emission groups (HH and HL) was significantly higher than that of the low GHG emission groups (LH and LL). To meet sustainability requirements, maize farmers should pursue lower CFY and CFI, which means that the same income and output will produce fewer GHGs and that the HL group meets these two conditions simultaneously.

Considering the input of organic and chemical fertilisers, both showed significant positive effects on CFY and CFI (Figures S4–S7). The HH group exhibited the highest chemical fertilisation amount and the LH group exhibited the highest organic fertilisation amount. Obviously, the high GHG emission groups (HH and LH) invested more fertiliser, but this input did not achieve sustainability. The LH group had the highest CFY and CFI values, followed by the HH group.

4.3 Uncertainties and limitations

Uncertainties in these findings originate from the system boundary and choice of emission factors. Accurately defining the entire agricultural production process is the key to accounting for agricultural carbon emissions (Lal, 2004). However, there is no unified system boundary in the LCA of maize planting and the accounting scope is still expanding. For

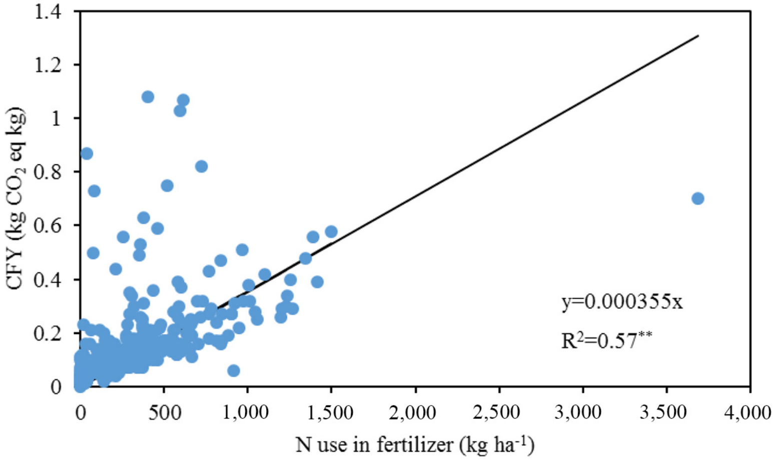


Figure 9. Correlation of CFY with N use in fertiliser

Note: The sparks (**) behind the number indicate the regression model has a statistically significant in the level of $p < 0.01$

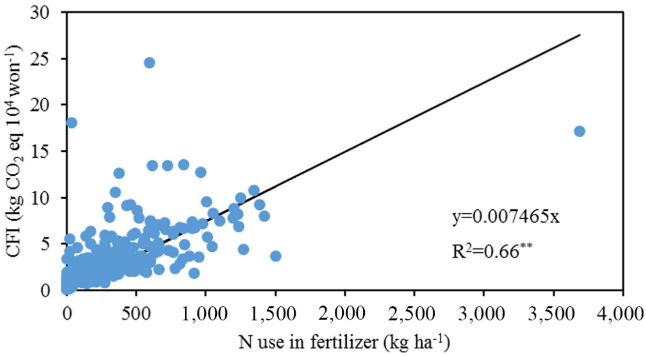


Figure 10. Correlation of CFI with N use in fertiliser

example, soil organic carbon was not included in this study. Therefore, the system boundary in this study may differ from the accounting boundary in prior research, which may lead to difficulty in comparing the calculated results. There are many studies on emission factors and the IPCC also has a recognised emission factor database; however, the database uses a large amount of planting data from the USA and Europe. For the intensive subsistence cultivation of maize, there is no targeted database that provides emission factors that are widely adopted worldwide. Scholars have used different emission factors in different studies. Comparing these studies without uniform standards may result in incompatible results. Using the questionnaire survey data, this study divided the direct and indirect emissions according to their inputs, which may also affect the calculated results. The factors influencing the CF were limited by the questionnaire items and were expanded to encompass a larger scope of socioeconomic development. However, some studies (Wang *et al.*, 2015; Yan *et al.*, 2015) have indicated that there is a synergistic relationship between economic development and CF.

4.4 Practical significance and policy implications

In this study, the yield of maize cultivation in South Korea was higher than that in other maize-producing regions, but the two functional units CFA and CFI were lower. This indicates that intensive subsistence maize cultivation in South Korea does not produce more CF while ensuring maize yield and the income of farmers, especially in the study area, as reinforced by the results of the HL group. This provides the following practical implications for maize-planting countries around the world in the face of climate change. The traditional perceptions of intensive subsistence cultivation should change; they do not always have high inputs and low outputs. This study showed that sustainable maize farming can be achieved through sound agricultural operations. Organic fertilisers should be used instead of chemical fertilisers. Fertiliser is the most important source of CF and the use of organic fertiliser can replace it and reduce GHG emissions. More importantly, the composting process results in carbon sequestration, which is important for carbon neutrality. The source of organic fertiliser is mostly animal manure, whereas maize and maize stalk are sources of feed for animals, creating a cycle and avoiding wasting resources.

Regarding policymakers, more attention should first be paid to the profits of maize farmers. Currently, it is difficult for farmers to profit from cultivation and the government should provide subsidies to maize farmers, which could come from the secondary and tertiary industries of maize. Maize processing and agro-tourism tend to generate higher added value and a percentage of this added value could be transferred to maize farmers, which will ensure the supply of maize. Second, optimal maize farming promotes concentrated and coherent operation. Scattered farmers fail to generate economies of scale when farming or wasting resources. The concentration of land can be controlled on a large scale through the power of cooperatives. Third is the development of modern agriculture. Through the use of modern farming techniques, it is possible to observe climatic trends, determine the best time for sowing, cob formation and harvesting, unifying farmers' operations, achieving pre-budgeting and saving production materials. Advanced agricultural machinery can also increase yield and clean energy tractors can reduce GHG emissions.

5. Conclusions

This study used the LCA CF calculation method with South Korean national-level questionnaire data and analysed the CF of maize planting under intensive subsistence cultivation in 2010, 2014 and 2019. The functional units in this research were the CFY and CFI. Over the past decade, there have been significant differences in the operating conditions (CFI, income, cost and profit) of maize households. In addition, the results indicated that the average CF of maize planting is 4,774.79 $kg\ CO_2\ eq\ ha^{-1}$, the average CFY is 0.17 $kg\ CO_2\ eq\ kg^{-1}$ and the average CFI is 3.56 $kg\ CO_2\ eq\ 10^4\ won^{-1}$. The use of N in chemical fertilisers contributed the most to CF (54%). Moreover, in terms of grouping, the HL group exhibited the lowest CFA and CFI, which was the most sustainable in comparison, whereas the LH group showed the opposite trend. The use of N, chemical and organic fertilisers was all significantly positively correlated with CFA and CFI. Therefore, in intensive subsistence cultivation conditions, as we face the risks of climate change, proper operation and selection of the correct input combination can effectively reduce GHG emissions and meet sustainable development requirements.

Note

1. The benchmark unit area for maize planting in the survey is 300 Pyeong. 300 Pyeong = 1,000 m^2. The inputs in this study were calculated based on 1 ha.

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