Journal of Cleaner Production 211 (2019) 742–748

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental performance of organic farming: Evidence from Korean small-holder soybean production

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ARTICLE INFO

Article history:
Received 2 June 2018
Received in revised form
7 November 2018
Accepted 8 November 2018
Available online 23 November 2018

Keywords:
Energy efficiency
Greenhouse gas emission
Life cycle assessment
Organic farming
Conventional farming
Multi-level regression

ABSTRACT

Organic farming has shown better environmental performance than conventional farming in many studies; however, no systematic study into intensive, smallholder farming practices in Asia has been conducted. In this study, the energy efficiencies (EEs) and greenhouse gas (GHG) emissions of organic and conventional soybean production systems in South Korea, and their major contributing factors, based on life cycle assessments (LCAs) are explored. Multi-level regression analyses and non-parametric comparison tests were applied to the data from 60 soybean farms, 30 of each production system. The results show that conventional farming (1.923 energy efficiency) is significantly more energy efficient than organic farming (1.046 energy efficiency). The energy inefficiency of organic farming is attributed to the excessive use of energy for fuel and mulch film, and smaller crop yields. Greenhouse gas emissions are not significantly different between the organic (2045.11 kg CO2 eq/ton) and conventional soybean-farming systems (1657.55 kg CO2 eq/ton). The surprisingly smaller EE and larger GHG emissions associated with soybean production in Korea, compared with those of large-scale farming, necessitates further research on the environmental performance of smaller farms in Asia.

1. Introduction

Organic farming is often perceived to be better for the environment than conventional farming; it is recognized as one of the most reasonable alternative farming systems for overcoming the challenges of climate change (Gomiero et al., 2008). The increasing importance of organic farming has sparked a range of comparative research into the environmental impacts of organic and conventional farming methods (Alonso and Guzman, 2010; Deike et al., 2008; Gelfand et al., 2010; Litskas et al., 2011; Mousavi-Avval et al., 2011; Petersen et al., 2006; Pimentel et al., 2005; Reganold et al., 2001; Seidel et al., 2017; Williams et al., 2006; Wood et al., 2006). Most research has supported the better environmental performance of organic farming (International Trade Centre and Research Institute of Organic Agriculture, 2007; Gomiero et al., 2008; Lynch et al., 2011); however, some studies have found that organic farming performs relatively poorly on an output basis, being less energy efficient and emitting higher levels of greenhouse gases. (Bertilsson et al., 2008; Gomiero et al., 2008; MacRae et al., 2010; Mondelaers et al., 2009; Skinner et al., 2014).

Several meta-analyses aimed at overcoming the conflicting energy performance results from individual comparative studies of organic and conventional farms have been conducted, though, the results remain inconsistent. In a review of 130 studies of farm-level energy use and global warming potential, Lynch et al. (2011) concluded that organic farming uses less energy and is more energy efficient than conventional farming with respect to both output and area. On the basis of their meta-analyses, Bengtsson et al. (2005), Mondelaers et al. (2009), Smith et al. (2014), and Tuomisto et al. (2012) concluded that conventional farming performed better per unit of output than organic farming. These inconsistent results are due to differences in farm characteristics and measurement and analytical techniques.

A large proportion (95%) of existing studies of farm energy efficiency (EE) and greenhouse gas (GHG) emissions rely on data from Europe, America, and Oceania, and only a few have used small-scale farm data from Asia (Lee et al., 2015). Consequently, the results may be biased toward large-scale farms (over 10 ha) that are characteristic of the former regions. Indeed, organic rice farms have poor EEs (Gil et al., 2008; Hokazono and Hayashi, 2012) and lower GHG

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https://doi.org/10.1016/j.jclepro.2018.11.075
0959-6526/

emissions (Ryu et al., 2012) compared to conventional farms in Korea and Japan (farm size < 2 ha), which is contrary to previous findings on large-scale farms. Hence, to determine the impact of farm characteristics on environmental performance, an expanded research base that includes studies of small-scale farms in Asia is required. Lee et al. (2015) also suggested that future research should employ larger samples from primary sources to improve confidence, as well as mono-crop farming for direct and unbiased comparisons.

In this study, the EE and GHG emissions of small-scale soybean farms in South Korea are evaluated, and the environmental performance of organic and conventional soybean farming systems are compared. We also examine and identify the farming components that contribute to differences in EE and GHG emissions between organic and conventional farming systems in terms of energy input categories, farming practices, and energy outputs. In Korea, certified organic soybean farms are relatively plentiful compared to other crops, which provides a large sample size and ensures statistical significance.

Previous studies on the environmental performance of soybean production have revealed higher EEs for conventional farming over organic farming (Zhang et al., 2015; Ferro et al., 2017), but were controversial in terms of GHG emissions (Knudsen et al., 2010; Abeliotis et al., 2013; Kamali et al., 2017). No previous study that compares the EEs or GHG emissions of organic and conventional soybean farms in Korea has been reported. We find surprisingly smaller EEs and larger GHG emissions associated with small-scale soybean production in Korea compared to those of large-scale farming.

2. Material and methods

In this study, we evaluate two main aspects of organic and conventional soybean farms in Korea. First, the characteristics of energy use and GHG emissions are examined on the basis of input categories and farming practices, respectively. Then, input variables that are strongly related to differences in EEs and GHG emissions between the two farming systems are identified by energy-input category and farming practice, respectively.

2.1. Data collection

We surveyed organic and conventional soybean farms. Data were collected using farm interviews (January–February of 2012) and verified against daily farming records and other documents. To minimize the potential impact of external factors unrelated to farm management practices, a set of prerequisites was established, as proposed by Alonso and Guzman (2010): (1) organic farms must have full certification for the sale of organic products, which requires over three years of organic farming practice, (2) pairs of organic and conventional farms must be located in close proximity and have similar biophysical conditions to avoid soil-type, climatic, and topographic biases, and (3) pairs of organic and conventional farms must have similar cultures and production cycles. On this basis, 76 soybean farms were identified for surveying in the northern provinces of Korea; they were separated into three groups that correspond to regions to the north, south, and east of Seoul. All locations were traditionally rural areas. Since there were fewer organic than conventional farms, the former were selected first, and conventional farms were chosen according to their proximities to organic farms. To ensure similar biophysical conditions and farming systems, the organic and conventional farms were usually on neighboring plots. We eliminated 16 farms from the comparative study due to incomplete or improper records, which left 60 farms, 10 organic and 10 conventional for each of the three locations (i.e., positions relative to Seoul).

The characteristics of the 60 farms are summarized in Table 1. As of 2012, the sample farms were slightly larger than the Korean average of 1.32 ha, while their soybean yields were slightly lower than the average of 1520 kg/ha, and the average owner age was slightly lower than the average of 64.4. The conventional soybean farms were larger than the organic farms and had high yields. The socioeconomic characteristics of the surveyed farms were compared, including location, age, and acreage for each farming system.

2.2. Environmental performance

To compare the environmental performance of organic and conventional soybean farms, we applied life cycle assessment (LCA) protocols. The LCA system boundaries in this study covered the production of input materials and the farming practices for the soybean-production stage of the crop season, as shown in Fig. 1. The flow of energy for each stage of the life cycle for soybean production is described in terms of the inputs associated with different farming practices. Inputs include machinery, fuel, fertilizers, seeds, pesticides, mulching plastic, and labor. Farming practices cover tilling, fertilizing, mulching, seeding, weeding, spraying, pruning, irrigating, harvesting, threshing, and screening. Post-screening practices involving residue management, storage, and transport, fell outside of the system boundaries.

Life cycle assessment was applied using energy coefficients and GHG emission factors that were obtained from previous studies and databases. The first step in determining the EE associated with soybean production involved evaluating energy inputs and outputs. The input and output materials for various farming practices were converted into input and output energy levels using energy coefficients. The energy coefficient is defined as the amount of energy per unit used to produce, maintain, and apply the material. Machinery, fuel, electricity, manure, seed, and labor are key inputs for both organic and conventional soybean production. In addition, conventional farming uses synthetic fertilizers and chemical pesticides, while organic farms use biological pesticides and mulch film. Organic farms also require more labor for weeding as the use of chemical herbicides is not permitted.

Energy coefficients for this study are based on average values used in previous studies and databases. Energy coefficients for machinery inputs, fuel, electricity, seeds for soybean and rye cover crops, mulch film, pesticides, fertilizer, and labor are listed in Table A1, along with the corresponding references. The energy coefficients for various machinery inputs reflect the total embodied energy associated with machine-based production, including raw materials, manufacture, repair and maintenance, and fuel consumption. In terms of fuel, the soybean farms surveyed in this study mostly used diesel for tilling, petrol for mower weeding and organic-fertilizer/pesticide spraying, and kerosene for weed burning, while electricity was used for harvesting, threshing, and screening.

The energy coefficients of seeds are based on the embodied energy consumed during their production, while energy coefficients for synthetic and compound fertilizers, including manure and organic fertilizers, are based on the relative proportions of nitrogen, phosphorus, and potassium that they contain. Many more pesticides and herbicides are sprayed for crop protection and weed suppression in conventional farming, whereas only a few biological pesticides (botanical extracts or microorganisms) are sprayed in organic farming, which relies on human labor for weeding. A diverse range of energy coefficients was used for fungicides, insecticides, and herbicides.

Farm-induced GHG emissions are provided in terms of the

Table 1
Characteristics of surveyed soybean farms.

Farming System	Average Age of Owner	Average Size (ha)	Average Yield (kg/ha)
Organic	60.8	1.36	1139
Conventional	60.3	1.88	1503
Average	60.5	1.62	1321

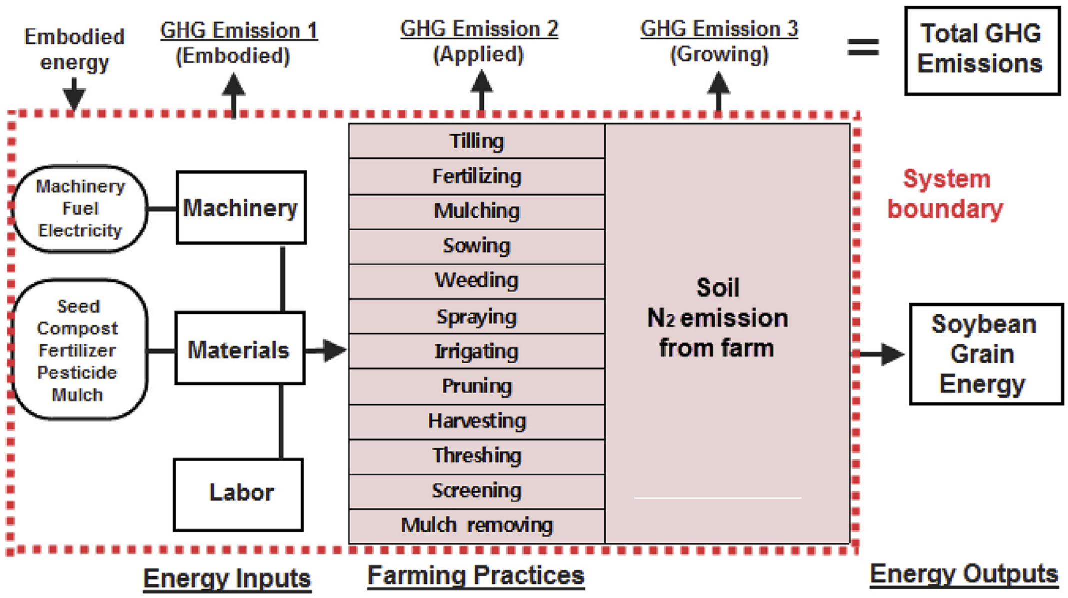

Fig. 1. Energy flows and greenhouse gas emissions for soybean farming.

carbon dioxide equivalency (kg CO2eq) of total gas emissions, including carbon dioxide, methane, and nitrous oxide. We used LCA to determine the GHG emissions at each life cycle stage during soybean production. Emissions from production inputs, which include all machinery and materials, and their applications to soybean production were determined using GHG conversion factors from previous studies and databases (Table A2). Hence, GHG emissions embodied within inputs, farming practices, and the growth of soybeans and cover crops, were included. The conversion factor of 0.94 kg CO2eq/kg for mulch film was obtained by deducting 1.00 kg CO2eq/kg from the 1.94 kg CO2eq/kg suggested by Hammond and Jones (2008), which reflects the suppression of GHG emissions due to soil coverage by the film. The conversion factors for fertilizer production and application were separated in order to reflect emissions from both stages. Both GHG conversion factor emissions for the growth of soybeans and rye in the green manure season were also considered.

2.3. Comparison and evaluation

The input energies used by organic and conventional farming were compared, as well as EEs and GHG emissions by input category and farming practice. Both Student's t-tests and Wilcoxon rank-sum tests were used to compare their respective environmental performances. We depended more on the Wilcoxon test, as the normality of most variables were rejected by the Shapiro-Wilk test. Multilevel models with random effects were applied to determine the impact of farm characteristics, including the farming system, location, age, and acreage, on EE and GHG emissions. Energy efficiency and GHG emission regressions with age and acreage were compared to multilevel model regressions of random intercept and slope with either location or farming system as the group variables that provide statistical confidence. All regressions used logarithms of EE, GHG emissions, and age variables to satisfy the normality condition of residuals. All statistical analyses were performed in R 3.5.0.

3. Results

3.1. Comparisons of energy use and energy efficiency (EE)

Average inputs for soybean farming practices are provided in Table 2. Organic farms were found to consume less pesticide, manure and fertilizer, but more mulch film, seeds, and fuel compared to conventional farming ($p < .05$). Mulch film is rarely used in conventional farming but it is extensively used to retain moisture and prevent weed growth in organic farming, and organic farms use more seeds due to cover cropping. Although organic farms utilize more machinery and labor, as well as less electricity, the differences were not statistically significant. Organic farming was also found to be significantly lower yielding ($p < .05$) than conventional farming, with average soybean yields of 1139.26 and 1502.99 kg/ha for organic and conventional farming, respectively.

The total input energy of each farm was obtained by summing the input energy of each category, which is the product of the input and the energy coefficient. Over 85% of the total energy consumed in soybean production was accounted for by manure and fertilizer, fuel, and mulch film, both per ton (Table 3) and per hectare (Table A3). The average input energy consumed by an organic soybean farm was 22,421 MJ/ton (22,568 MJ/ha), which is significantly more than the 13,416 MJ/ton (17,832 MJ/ha) consumed by a conventional farm, as summarized in Table 3, and contrary to the results of previous studies (Bertilsson et al., 2008; Gomiero et al., 2008; Lynch et al., 2011; MacRae et al., 2010; Mondelaers et al.,

Table 2
Average Inputs per ha for soybean production.

Inputs	Organic (O)	Conventional (C)	O-C	t_{O-C}	p_w
Machinery (H)	69.93	65.43	4.50	0.353	0.492
Fuel (L)	182.88	144.78	38.10	1.616	0.006***
Electricity (kw)	20.54	25.98	−5.44	−0.712	0.315
Seeds (kg)	92.90	45.78	47.12	2.812	0.048**
Manure & fertilizers (kg)	3688.40	4316.43	−628.03	−0.788	0.022**
Bio & chemical pesticides (kg)	0.14	4.02	−3.88	−6.306	<0.001***
Mulch film (kg)	82.97	17.28	65.69	5.270	<0.001***
Labor (h)	508.06	480.76	27.30	0.326	0.279
Yield(kg)	1139.26	1502.99	−363.72	−2.116	.080*

t_{O-C} = t value for O-C (n = 30), p_W = Wilcoxon test p-value, *p < .10, ** for p < .05, *** for p < .01.

Table 3
Comparison of Average input energy by category (MJ/ton).

Input category	Organic (O)	Conventional (C)	O-C	t_{O-C}	p_w
Machinery & Supplies					
Machinery	903.89	556.33	347.56	2.520**	<.001***
Fuel	6948.31	4189.97	2758.34	2.648**	<.001***
Electricity	271.30	235.83	35.47	-.324	.076*
Material					
Seeds	891.28	330.62	560.66	2.672**	.003***
Manure & fertilizers	6391.22	5695.83	695.39	.575	.476
Bio & chemical pesticides	22.65	1145.29	−1122.64	−4.524***	<.001***
Mulch film	6373.32	887.54	5485.78	4.861***	<.001***
Labor	618.76	375.92	243.84	2.988***	.011**
Total Input Energy/ton	22,420.72	13416.33	9004.39	3.216***	<.001***
EE	1.046	1.923	-.877	−3.904***	<.001***

t_{O-C} = t value for O-C (n = 30), p_W = Wilcoxon test p-value, *p < .10, ** for p < .05, *** for p < .01.

2009). Organic farms were found to use more energy in terms of mulch film, fuel, seeds, machinery, and labor, but less energy for pesticides and electricity; these differences were statistically significant, and are shown in Table 3. Compared to conventional farms, the higher input energies associated with organic farms were largely due to the high energies associated with the use of mulch film and fuel, which reduced the EEs of organic farms, as well as lowered soybean yields. Organic farms consumed less energy for manure and fertilizers, but not significantly less than conventional farms.

The input energy consumed during each farming practice stage in organic and conventional farming is compared in Table A4. Tilling, fertilizing, and mulching accounted for over 75% of the total energy consumed during soybean production. Organic farms consumed more energy for mulching, seeding, irrigation, and screening, and less energy for spraying and weeding compared to conventional farms; these differences were also statistically significant. Although organic farming saved input energy for fertilizing, the difference between the two farming practices was not statistically significant. The additional amount of energy used for mulching in organic farming was greater than the energy saved in tilling, fertilizing, weeding, spraying, pruning, and harvesting, when compared to conventional farming.

The lower soybean yield and the greater input energy used in organic farming resulted in a significantly lower EE (1.046) compared to that for conventional farming (1.923) (Table 3). The results were further validated by likelihood testing using ordinary least-squares (OLS) regressions against multilevel regressions. The test results rejected the OLS regression of EE on farm characteristics (owner age and farm size) against the random intercept and slope regression, with farming system as the group variable, which supports the significance of the impact of the farming system on EE ($p < .01$). The random-effects regression revealed that other farm characteristics did not significantly impact the EE. However, the likelihood test failed to reject the OLS regression against the random-effects regression using the location variable, confirming that location did not have a significant impact on EE. These results support our sampling methodology that compares farms with similar biophysical conditions, as proposed by Alonso and Guzman (2010).

3.2. Greenhouse gas (GHG) comparison

Greenhouse gas emissions were compared by input category, as summarized in Table 4. Manure, fertilizers, and fuel accounted for more than 85% of the total GHG emissions during soybean production. Hence, N2O emissions associated with the on-farm nitrogen cycle, which uses animal manure and synthetic fertilizers, and CO2 emissions from fossil fuel, were the major contributors to GHG emissions during soybean production. The use of fuel, fertilizers, and manure needs to be controlled in order to mitigate GHG emissions. Organic farms were found to emit fewer GHGs from manure and fertilizers, but the differences between organic and conventional farms in this regard are not statistically significant. Organic farms also emitted more GHGs from fuel, mulch film, growth, machinery, and seeds, but less from pesticides, and these differences were statistically significant. The GHG emissions from seeds appeared to be higher in organic farms, which was ascribed to the use of cover crops (rye).

The GHG emissions in each stage of organic and conventional farming practices are compared in Table A5. Tilling and fertilizing accounted for over 75% of the total GHG emissions, irrespective of the farming system, which supports their important roles in the production of GHGs during soybean production. Organic farms emitted more GHGs from mulching and threshing, but less from weeding and spraying, and the differences were statistically significant. Even though organic farming emitted less GHGs through fertilizing, accounting for the largest difference in the GHG

Table 4
OLS and multi- level models regressions of EE.

	OLS	MLM with Location as group	ML with Farm System as group
Fixed			
intercept (β_0, γ_{00})	−0.261(0.985)	−0.604(1.207)	−0.413(0.897)
Age (β_1, γ_{10})	0.006(0.008)	−0.001(0.009)	0.007(0.008)
Area_log (β_2 γ_{20})	0.010(0.073)	0.094(0.104)	0.020(0.065)
Random			
intercept ($\sigma^2_{\mu_{0j}}$)		0.0382(0.0772)	0.0573(0.028)
Age ($\sigma^2_{\mu_{1j}}$)		0.0001(0.0001)	0.0001(0.0001)
Area_log ($\sigma^2{}_{\mu_{2j}}$)		0.0001(0.0001)	0.0014(0.0001)
Residual ($\sigma^2_{\varepsilon_{ij}}$)		0.360(0.069)	0.300(0.054)
Evaluation (Test)		(vs OLS)	(vs OLS)
-2 log(lh)	108.501	107.899	100.060
		0.602	8.441
		0.896	0.004***

( ) for standard error. P_{test} = Likelihood test against OLS, *p < .10, ** for p < .05, *** for p < .01.

emissions between the two systems, it was statistically insignificant.

Overall, organic soybean farming produced 23.4% more GHG emissions per ton of yield (2045.11 kg CO2eq/ton) compared to conventional farming (1657.35 kg CO2eq/ton); however, the differences were not statistically significant, as shown in Table 5. The results were validated further by likelihood testing using OLS regressions against multilevel regressions. The test result failed to reject the OLS regression of GHG emissions on farm characteristics (owner age and farm size) against either the random intercept and random slope regression, with farming system as the group variable, or the random-effects regression, with location as the group variable (Table 6). These results favor the OLS regression over both random-effects models and reject any significant impact of farming system or location on GHG emissions. The OLS regression also revealed that other farm characteristics did not significantly impact GHG emissions.

4. Discussion

The poorer EE of organic farming compared to conventional farming (54.4%) identified in this study contradicts the results of previous studies. Pimentel et al. (2005) found that organic methods were more energy efficient (120.4%), based on experiments involving US soybean farms, and Taylor (2000) also found a higher EE (102.8%) for organic farms, based on the analysis of secondary data from German soybean farms. Higher EEs have also been reported for organically farmed field crops in Europe and North America (Gomiero et al., 2008; Lee et al., 2015; Lynch et al., 2011). The lower soybean yields and the higher input energies, especially for fuel and mulch film, associated with organic farming resulted in a significantly lower EE in this study. However, the low EEs of organic farms are less surprising in the context of smaller, intensive, field-crop farming systems, especially in Asia (Gil et al., 2008; Hokazono et al., 2009, 2012; Zhang et al., 2015). The EEs for soybean production (1.046 for organic and 1.923 for conventional) in Korea are lower than large-scale farming in other countries including China. Zhang et al. (2015) estimated EEs of 1.34 for organic farming and 12.10 for conventional farming for farm sizes over 30 ha in soybean production in China. These results also support those of Mohammadi et al. (2013), who found that EE increased in crop farming with increasing farm sizes.

Greenhouse gas emissions are not statistically affected by the different farming systems for soybean production in Korea. Although organic farming emits 23.4% more GHGs than conventional farming, the difference is not statistically significant. Organic farms emit significantly more greenhouse gases that are associated with seeds, fuel, and mulch film. The results partly favor previous studies, which have shown more GHG emissions per unit of output for organic farms (Bertilsson et al., 2008; Gomiero et al., 2008; Lynch et al., 2011; MacRae et al., 2010; Mondelaers et al., 2009). The GHG emissions for soybean production in Korea are surprisingly large compared to those in Canada (218.95 kg CO2eq/ton; Pelletier et al., 2008) and Brazil (275.64 kg CO2eq/ton, Kamali et al., 2017; 186 kg CO2eq/ton, Raucci et al., 2015). These results confirm that smallholder farming in Asia tends to be very intensive, which results in heavy GHG loadings, irrespective of the farm management system. Bos et al. (2014) found the high intensity level as the most likely cause for higher energy use and GHG emissions for crop production.

We found that the largest contributors to the poor EE and GHG emission performance for Korean soybean production are manure, fertilize, and fuel. Mulch film for organic farming further contributes to this poor performance. These inputs need to be controlled in

Table 5
Comparison of Average GHG emissions for input categories and growing (kg CO_2eq/ton).

Inputs (Categories)	Organic (O)	Conventional (C)	O-C	t_{O-C}	p_w
Machinery & supplies					
Machinery	75.02	46.18	28.85	2.520**	<.001***
Fuel	501.06	301.32	199.75	2.644**	.001***
Electricity	14.67	12.55	2.13	.364	.074*
Material					
Seeds	433.72	193.09	240.62	1.338	.010**
Manure & fertilizers	873.32	982.39	−109.08	-.523	.935
Bio & chemical pesticides	1.63	82.70	−81.07	−4.529***	<.001***
Mulch film	79.88	11.12	68.76	4.861***	<.001**
Growing	65.81	28.21	37.60	2.466**	.013**
Total GHGE/ton	2045.11	1657.35	387.55	1.116	.398

t_{O-C} = t value for O-C (n = 30), p_w = Wilcoxon test p-value, *p < .10, ** for p < .05, *** for p < .01.

Table 6
OLS and Multi- Level Models Regressions of GHG emission (ton).

	OLS	MLM with Farm System as group	ML with Location as group
Fixed			
intercept (β_0, γ_{00})	0.059(1.055)	0.153(1.038)	0.265(1.198)
Age (β_1, γ_{10})	−0.004(0.009)	−0.0002(0.009)	−0.004(0.008)
Area_log (β_2 γ_{20})	0.062(0.078)	−0.029(0.083)	0.043(0.102)
Random			
intercept ($\sigma^2_{\mu_{0j}}$)		0.0500(0.0793)	0.1885(0.110)
Age ($\sigma^2_{\mu_{1j}}$)		0.0001(0.0001)	0.0001(0.0001)
Area_log ($\sigma^2_{\mu_{2j}}$)		0.0005(0.0002)	0.0025(0.001)
Residual ($\sigma^2_{\varepsilon_{ij}}$)		0.3940(0.0745)	0.3997(0.081)
Evaluation (Test)		(vs OLS)	(vs OLS)
−2 log(lh)	130.944	129.403	130.810
		1.542	0.134
		0.214	0.714

( ) for standard error, P_{test} = Likelihood test against OLS, *p < .10, ** for p < .05, *** for p < .01.

order to improve EE and mitigate GHG emissions in the future. Animal manure, which replaces synthetic fertilizers in organic farming, is a significant source of nitrous oxide, and results in higher GHG emissions. Accordingly, the substitution of manure for synthetic fertilizers is not recommended as an alternative for organic farming. Practical strategies for mitigating climate change can be derived by transforming nitrogen-based production systems into carbon-based systems, such as invigoration by carbon sequestration and biochar farming. However, the unconditional reduction or termination of nitrogen-based ingredient inputs will cause a sharp decrease in productivity, leading to low EE.

The use of mulch film for weed control has contributed greatly to lowering EE and raising GHG emissions in organic production, which is ascribable to the high energy coefficient and GHG conversion factor of mulch film compared to other inputs. Renewable mulch paper, which has a low energy coefficient, can be used to replace plastic mulch film in organic farming. These results indicate that the energy coefficient and GHG conversion factor of an input material is a significant determinant of energy consumption and GHG emissions. Therefore, the selection of input materials with lower energy coefficients and conversion factors will enhance EE and mitigate GHG emissions; the importance of this cannot be neglected in climate change mitigation strategies.

5. Conclusion

The EEs and GHG emissions associated with organic and conventional soybean farming were compared in detail by input category, farming practice, and outputs, for different farming components. The results show that conventional farming is significantly more energy efficient than organic farming. The poor EEs of organic soybean farms in Korea are clearly demonstrated by their higher input energy consumptions and lower output energy productions compared to conventional farms. Organic soybean farms also produce more GHG emissions than conventional farms per output unit, although the differences are not statistically significant.

The poor EE performance of organic farms in Korea are different to the results of previous studies with large-scale farming. The surprisingly smaller EE and larger GHG emissions associated with soybean production in Korea compared to those of large-scale farms demand further study on the environmental performance of smaller farms throughout Asia. The significant contributors to poor environmental performance in Korean soybean farming, namely manure, fertilize, fuel, and mulch film, need to be controlled to improve EE and GHG emissions in the future. To explain the differences in the environmental impacts of conventional and organic smallholder farming systems in Asian countries, more research into different farm products, using a range of environmental performance indicators, is required.

Acknowledgements

This research was supported by the MSIT(Ministry of Science, ICT), Korea, under the ITRC(Information Technology Research Center) support program (IITP-2018-2018-1-00877) supervised by the IITP(Institute for Information & communications Technology Promotion).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.11.075.

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