The Pennsylvania State University and Rodale Institute

Rodale Institute Farming Systems Trial (FST) cropping systems energy and greenhouse gas analysis using the Farm Energy Analysis Tool (FEAT)

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1. Introduction

There is an increasing interest in evaluating agricultural operations in terms of energy and greenhouse gas (GHG) emissions. First, cheap energy is becoming scarcer, encouraging farmers and researchers to think about new ways to use energy more efficiently. Second, global warming is increasingly being recognized as a major threat; understanding how agricultural systems are contributing to and, where possible, mitigating greenhouse gas emissions has become essential.

The Rodale Institute, one of the leading organic farming research organizations, commissioned this study to understand how organic and conventional field cropping systems differ in terms of energy and GHG emissions.

2. Objective

The objective of this study was to evaluate the Rodale Farming Systems Trial (FST) cropping systems in terms of energy and GHG emissions.

3. Methodology

The analysis was performed using the Farm Energy Analysis Tool (FEAT) (Camargo, Ryan, & Richard, 2011). For this study the FEAT model was updated to include composting energy and GHG emissions calculations. Tables 1, 2, and 3 have the additional equations and variables for this analysis. Rodale's FST includes six cropping systems: four organic and two conventional (Figure 1 and Table 4).

Table 1 – Equations for composting energy and GHG calculations

$$F_{compost\_prod} = \sum_i \frac{CR_i \times A_i \times E_{comp\_electr}}{Electr_{efficiency}} + CR_i \times A_i \times E_{comp\_fuel} \times ED$$

$$F_{compost\_transp} = \sum_i CR_i \times A_i \times Dist \times C_{transp} \times ED$$

$$GHG_{compost\_prod} = \sum_i CR_i \times A_i \times Em_{electr} + CR_i \times A_i \times E_{comp\_fuel} \times EmD$$

$$GHG_{compost\_transp} = \sum_i CR_i \times A_i \times Dist \times C_{transp} \times EmD$$

$$GHG_{N2O\_compost} = \sum_i NC_i \times A_i \times EF1 \times C_{N2O} \times GWP_{N2O} + \\ + \sum_i NC_i \times A_i \times EF3 \times EF5 \times C_{N2O} \times GWP_{N2O} + \sum_i NC_i \times A_i \times L \times EF4 \times C_{N2O} \times GWP_{N2O}$$

Table 2. Model parameters specifications used in equations from Table 1

Symbol	Units	Explanation
A_i	ha	field area for the ith crop
C_{N2O}	dimensionless	N2O-N to N2O conversion
C_{transp}	L ha-1 km-1	compost transportation energy
CR_i	kg ha-1yr-1	annual compost application rate for the ith crop
E_{comp_electr}	MJ kg-1 WM	electricity energy for compost production
E_{comp_fuel}	L kg-1 WM	fuel energy for compost production
ED	MJ L-1	energy embodied in the fuel
EF1	kg N2O-N kg-1 N	N2O-N emission factor from N additions from mineral fertilizer, crop residues and composting
EF3	kg N2O-N kg-1 NH3-N + NOX-N	N2O-N emission factor from NH3-N and NOX-N volatilized
EF4	kg N2O-N kg-1 N	N2O-N emission factor from N leaching and runoff
EF5	kg NH3-N + NOX-N kg-1 N	NH3-N and NOX-N volatilized emission factor from N additions from compost
$Electr_{efficiency}$	MJ MJ-1	electricity efficiency
Em_{electr}	kg CO2e MJ-1	GHG emissions per MJ of electricity
$GHG_{compost\_prod}$	kg CO2e yr-1	annual GHG emissions for compost production
$GHG_{compost\_transp}$	kg CO2e yr-1	annual GHG emissions from compost transportation
$GHG_{N2O\_composting}$	kg CO2e yr-1	annual GHG emissions from N2O from composting N

Table 3. Additional parameter references.

Type	Value	Unit	Variable	Ref[1]
Composting transportation	5.2×10^{-6}	L kg^{-1} km^{-1}	C_{transp}	a
Composting production energy[2]	0.00058 / 0.000468	L kg^{-1}/ MJ kg WM	E_{comp_fuel} / E_{comp_electr}	b
Composting N content	0.0048	kg N kg^{-1} WM	NC_i	c
Electricity efficiency	0.392	MJ MJ^{-1}	$Electr_{efficiency}$	d
Electricity emissions	0.18	kg CO_2e MJ^{-1}	Em_{electr}	e, f, g, h, i
N_2O-N emission factor from N additions from composting	0.01	kg N_2O-N kg^{-1} N	EF1	j

[1] References: a. van Haaren, Themelis, & Barlaz (2010) b. Sharma and Campbell (2007); c. Mangan et al. (1996); d. Wang et al. (1999); e. Wang (2001); f. Lewandowski et al. (1995); g. Shapouri et al. (2002); h. West and Marland (2002); i. Heller et al. (2004); j. IPCC (2006).

[2] Representing the composting diesel fuel and electricity respectively, not accounting for receival, shredding, screening, and dispatch reported in the study.

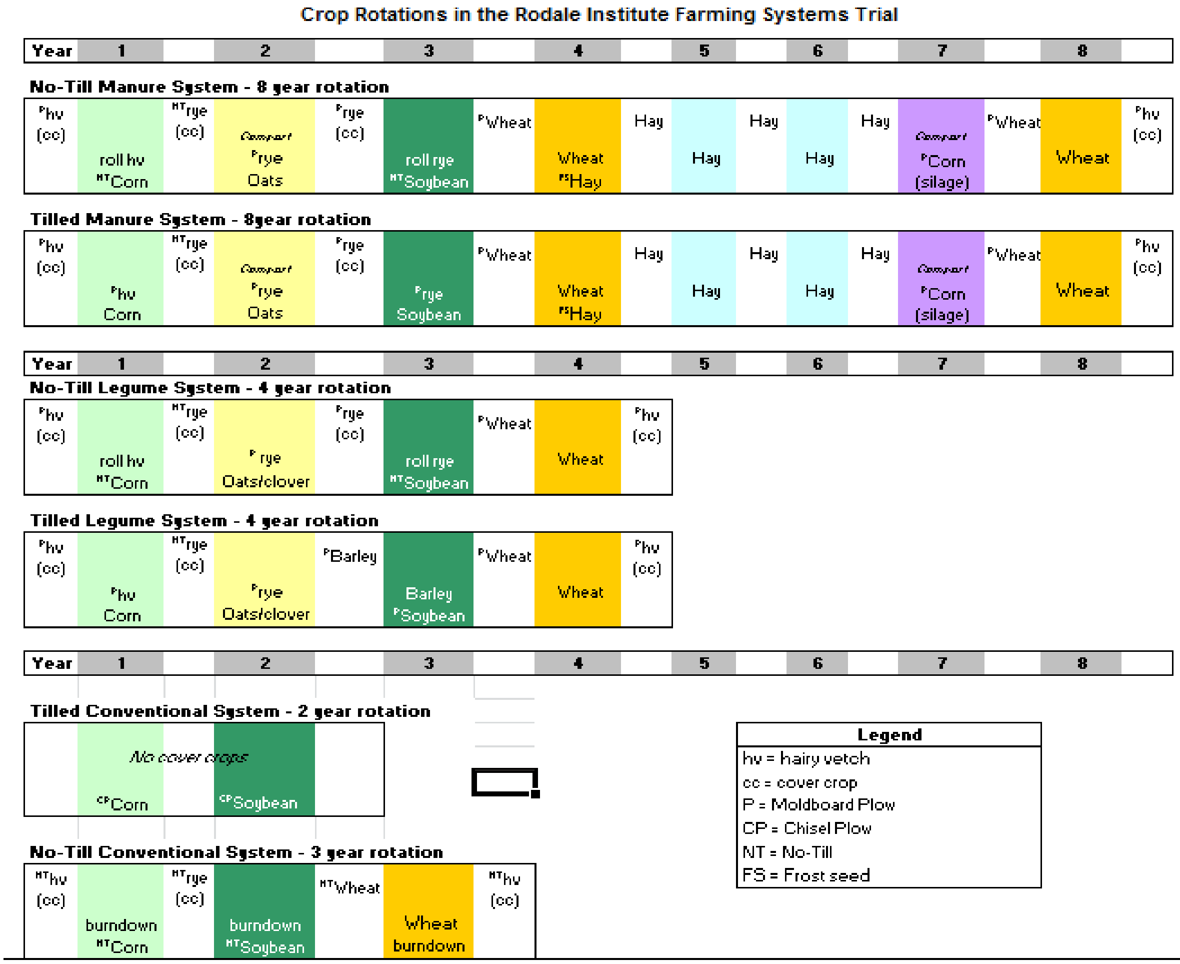

Figure 1. Crop rotations in the Rodale Institute Farming Systems Trial

Table 4. FST cropping systems nomenclature.

Name	Nomenclature
Organic manure tilled	CS1-CTM
Organic manure no-till	CS2-NTM
Organic legume tilled	CS3-CTL
Organic legume no-till	CS4-NTL
Conventional tilled	CS5-CTC
Conventional no-till	CS6-NTC

4. Results

4.1 Energy results

Across all organic cropping systems, the single greatest energy use component was diesel fuel, which ranged from 66 L ha^{-1} yr^{-1}(39% of total energy) in organic legume no-till (CS4-NTL) to 98 L ha^{-1} yr^{-1} (48% of total energy) in organic legume tilled (CS3-CTL) (Table 5 and Figure 2). The single greatest energy use component across the two conventional cropping systems was nitrogen fertilizer, representing 43% and 39% of the total energy for the conventional tilled and no-till respectively. The energy requirement (and also greenhouse gas emissions) associated with agricultural inputs are calculated based on their embedded energy and emissions required to produce that input.

Energy usage was lower for organic cropping systems mainly because of the use of alternatives to nitrogen fertilizer. Total energy use ranged from 7,474 to 11,955 MJ ha^{-1}yr^{-1}, with the no-till manure having the lowest followed by no-till legume < tilled manure < tilled legume < tilled conventional < no-till conventional (Figure 2, Table 5). Energy inputs from seeds were lower in the two manure systems compared to the two legume systems due to the perennial hay crop in that rotation. Fuel use and labor were lower in the no-till manure than in the tilled manure system because of the reduced field operations for corn and soybeans. On the other hand, both conventional systems had about the same total energy consumption. As mentioned above, nitrogen fertilizer was responsible for the biggest portion in energy use in both tilled and no-till conventional. Seed energy and diesel fuel were the next biggest contributors in energy use in both conventional systems. However the tilled conventional system had low seed energy and high diesel fuel inputs, while those two parameters were reversed in the conventional no-till system.

In addition to quantifying the energy requirements associated with crop production, crop outputs need to be considered and comparisons made in terms of production efficiency. A ratio between energy input and crop yield output was used to compare the cropping systems (Table 6). The energy input/ crop output ratio ranged from 1.63 to 2.73 MJ kg^{-1}dry matter (DM), with no-till manure exhibiting the best ratio and no-till conventional exhibiting the worst (Figure 3).

Table 5. Energy inputs for each cropping system

Energy inputs (MJ ha^{-1} yr^{-1})	CS1-CTM	CS2-NTM	CS3-CTL	CS4-NTL	CS5-CTC	CS6-NTC
N	0	0	0	0	4,938	4,605
P_2O5	0	0	0	0	195	130
K_2O	102	102	102	102	118	118
Compost transport	14	14	0	0	0	0
Compost production	229	229	0	0	0	0
Lime	203	203	203	203	243	243
Seed	1,865	1,865	2,639	2,839	1,357	2,547
Herbicide	0	0	0	0	732	1,050
Transportation of inputs	322	322	384	396	384	491
Equipment	849	866	748	725	635	594
Diesel fuel	3,890	3,312	4,380	2,941	2,418	1,853
Labor	693	563	614	329	456	324
Total	**8,166**	**7,474**	**9,070**	**7,534**	**11,473**	**11,955**

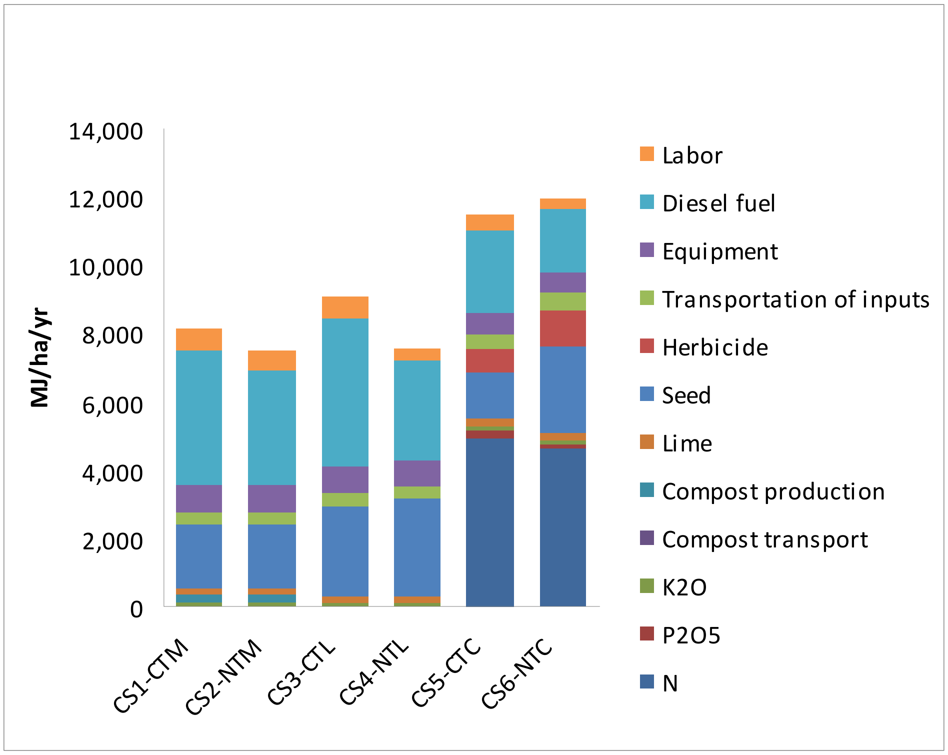

Figure 2. Energy inputs for each cropping system.

Table 6. Ratio between crop input energy and yield crop output.

Cropping systems	Input ($MJha^{-1}yr^{-1}$)	Output ($kgDMha^{-1}yr^{-1}$)	Ratio ($MJ\ kg^{-1}DM$)	Percent
CS1-CTM	8,166	4,788	1.71	62%
CS2-NTM	7,474	4,588	1.63	60%
CS3-CTL	9,070	4,162	2.18	80%
CS4-NTL	7,534	2,880	2.62	96%
CS5-CTC	11,473	4,641	2.47	91%
CS6-NTC	11,955	4,377	2.73	100%

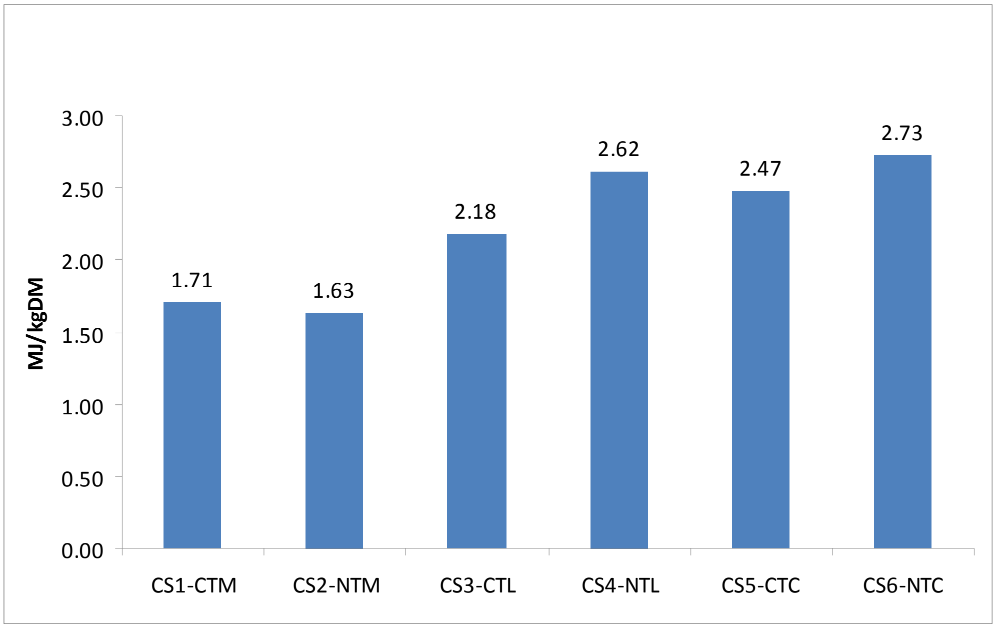

Figure 3. Ratio of the energy input (MJ) and crop yield (kgDM).

To summarize the results of the analysis, the four organic systems and two conventional systems were averaged and the organic versus conventional were compared in terms of energy inputs and ratios (Table 7 and Figures 4 and 5). Organic systems had an energy usage of 8,061 MJ $ha^{-1}yr^{-1}$, a 31% lower energy input than conventional systems (11,714 MJ $ha^{-1}yr^{-1}$). The energy input/ crop output ratio, in which smaller values are better, were 2.03 for organic systems and 2.60 for conventional systems, meaning it took 2.03 MJ to produce 1 kg of dry matter in the organic systems vs. 2.60 MJ in the conventional systems. In other words, production efficiency was 28% higher in the organic systems than in the conventional systems.

Table 7. Energy inputs for organic and conventional

Inputs	Organic (MJ ha^{-1} yr^{-1})	Conventional (MJ ha^{-1} yr^{-1})
N	0	4,771
P_2O5	0	163
K_2O	102	118
Compost transport	7	0
Compost production	114	0
Lime	203	243
Seed	2,302	1,952
Herbicide	0	891
Transportation of inputs	356	437
Equipment	797	614
Diesel fuel	3,631	2,135
Labor	550	390
Total	**8,061**	**11,714**

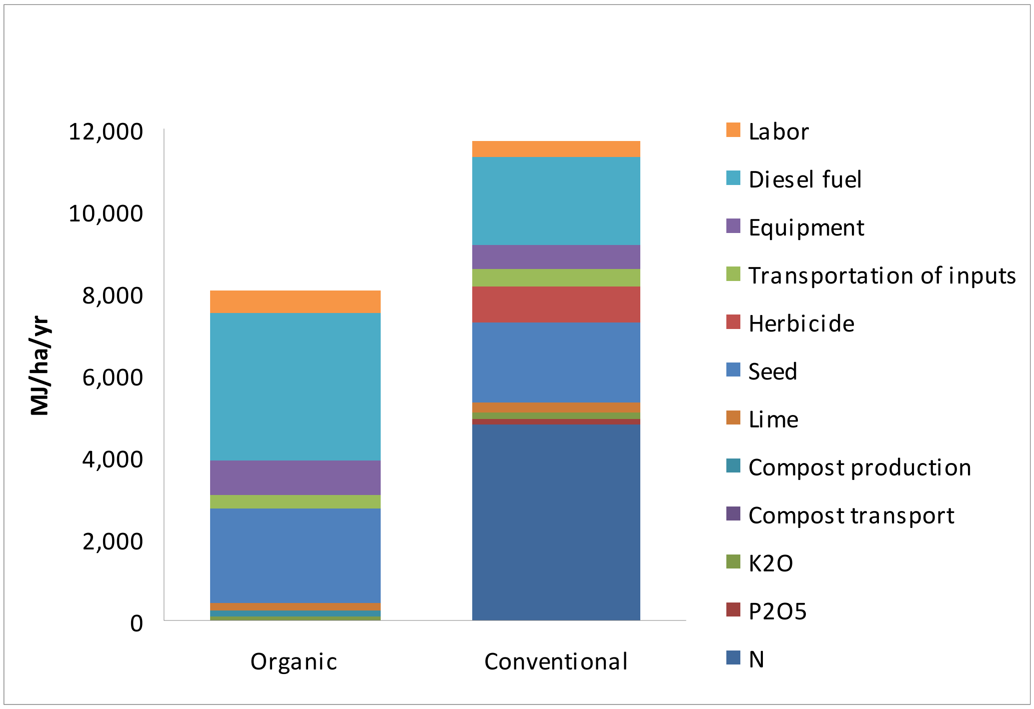

Figure 4. Energy inputs comparison between organic and conventional systems.

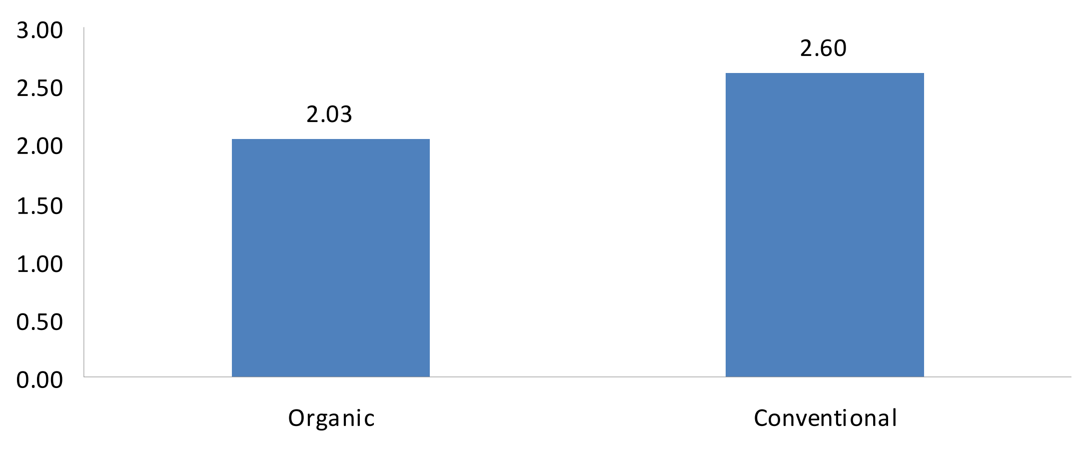

Figure 5. Ratio of energy input (MJ) per crop yield (kg DM) for organic and conventional systems.

4.2. Greenhouse gas emissions results

GHG emissions from cropping system inputs ranged from 905 to 1,635 kgCO_2e ha^{-1} yr^{-1}, with no-till legume having the lowest followed by tilled legume < no-till manure < tilled manure < tilled conventional < no-till conventional. The ratio between GHG emissions from input and crop yield output was also used to compare the cropping systems (Table 9). The GHG emissions per crop output ratio ranged from 0.22 to 0.37 kgCO_2e kg^{-1}DM, with tilled legume exhibiting the best ratio and no-till conventional exhibiting the worst (Figure 7).

Across all cropping systems, the major GHG input contributor was nitrous oxide (N_2O) emissions, due to soil processes associated with N in mineral fertilizer, crop residues, and compost. N_2O emissions ranged from 303 kg CO_2e ha^{-1} yr^{-1} (33% of total) in the tilled legume system to 807 kg CO_2e ha^{-1} yr^{-1} (49% of the total) in the no-till conventional system (Table 8 and Figure 6). CO_2 emissions associated with nitrogen production (where synthetic N fertilizer was used) and on-farm fuel use were the second and third highest categories of greenhouse gas emissions in terms of overall impact.

Table 8. Greenhouse gas emissions from cropping systems inputs.

GHG input emissions (kg CO_2e ha^{-1} yr^{-1})	CS1-CTM	CS2-NTM	CS3-CTL	CS4-NTL	CS5-CTC	CS6-NTC
N	0	0	0	0	323	302
P_2O_5	0	0	0	0	17	11
K_2O	8	8	8	8	9	9
Compost transport	1	1	0	0	0	0
Compost production	17	17	0	0	0	0
Lime	75	75	75	75	90	90
Seed	100	100	137	142	90	133
Herbicide	0	0	0	0	54	77
Transportation of inputs	17	17	20	21	20	26
Equipment	55	56	49	47	41	39
Diesel fuel	295	252	333	223	184	141
N_2O from N and compost	552	586	303	389	738	807
Total	**1121**	**1112**	**925**	**905**	**1566**	**1635**

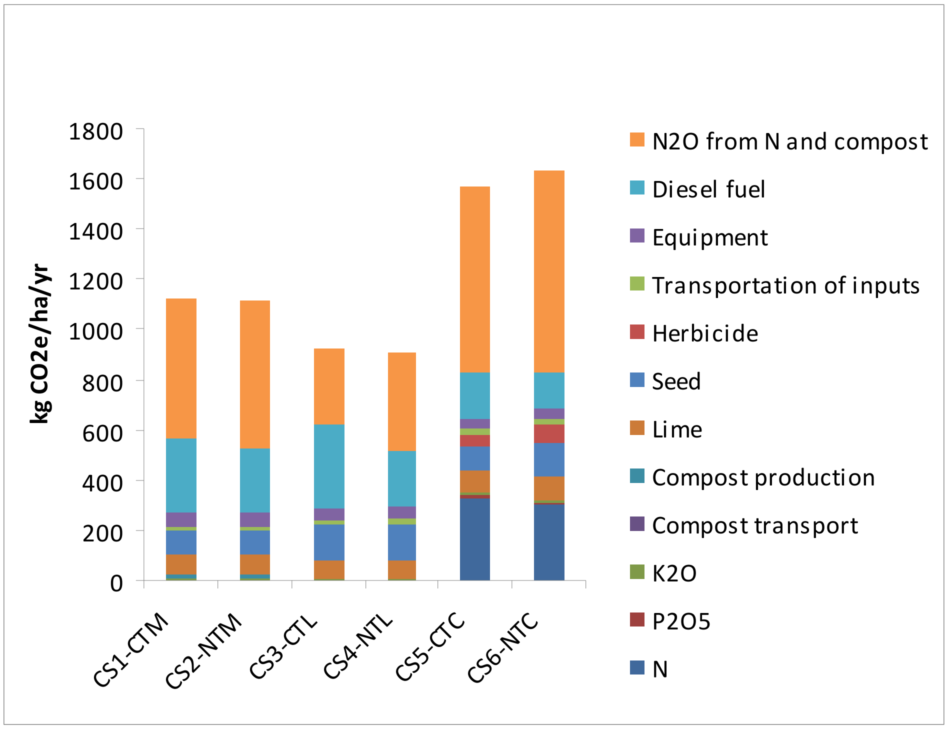

Figure 6. Greenhouse gas emissions from cropping systems inputs.

Table 9. Ratio between crop input greenhouse gas emissions and yield crop output.

Cropping systems	Input ($kgCO_2e\ ha^{-1}yr^{-1}$)	Output ($kgDMha^{-1}yr^{-1}$)	Ratio ($kgCO_2e\ kg^{-1}DM$)	Percent
CS1-CTM	1,121	4,788	0.23	63%
CS2-NTM	1,112	4,588	0.24	65%
CS3-CTL	925	4,162	0.22	59%
CS4-NTL	905	2,880	0.31	84%
CS5-CTC	1,566	4,641	0.34	90%
CS6-NTC	1,635	4,377	0.37	100%

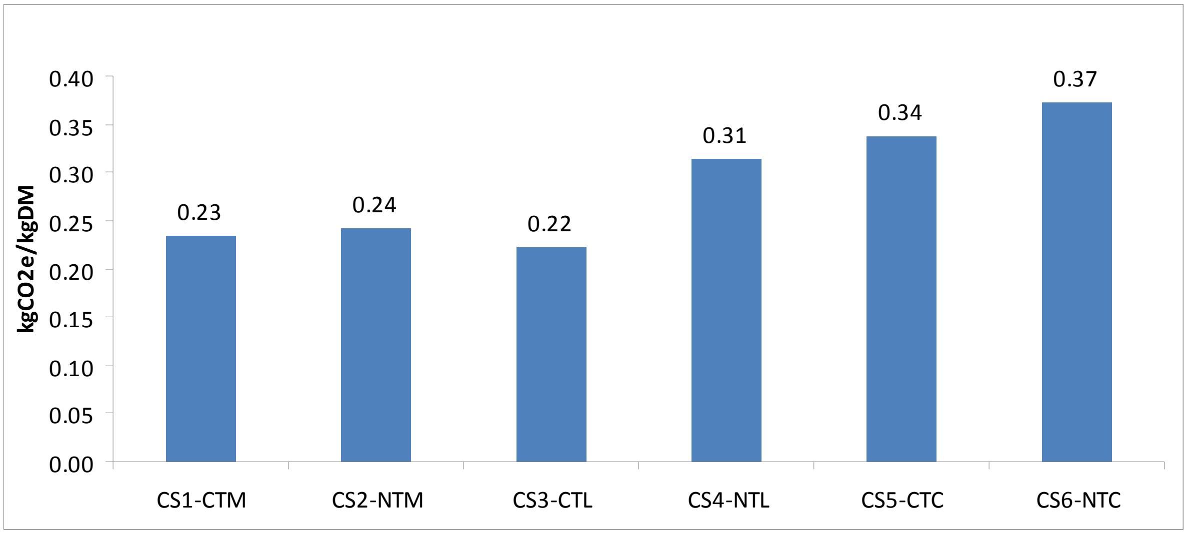

Figure 7. Ratio of greenhouse gas emissions from inputs per crop yield.

As in the energy analysis, the results of the analysis of the four organic systems and two conventional systems were averaged and organic vs. conventional systems compared (Table 10 and Figure 8). Organic systems had GHG emissions of 1,016 $kgCO_2e\ ha^{-1}yr^{-1}$, a 37% lower energy input than conventional systems (1,601 $kgCO_2e\ ha^{-1}yr^{-1}$). When the ratio of GHG emissions between inputs and crop outputs is calculated, the results show that the organic systems emitted 0.25 kg CO_2 equivalents per 1 kg of dry matter produced vs. 0.36 kg CO_2 equivalents per 1 kg of dry matter produced in the conventional systems. This means, per crop unit the organic systems emitted 40% less GHG than the conventional systems (Figure 9).

Table 10. Greenhouse gas emissions of inputs from organic and conventional systems.

Inputs	**Organic**	**Conventional**
N	0	312
P_2O_5	0	14
K_2O	8	9
Compost transport	1	0
Compost production	9	0
Lime	75	90
Seed	120	112
Herbicide	0	65
Transportation of inputs	19	23
Equipment	52	40
Diesel fuel	276	162
N_2O from N and compost	458	772
Total ($kgCO_2e\ ha^{-1}yr^{-1}$)	**1,016**	**1,601**

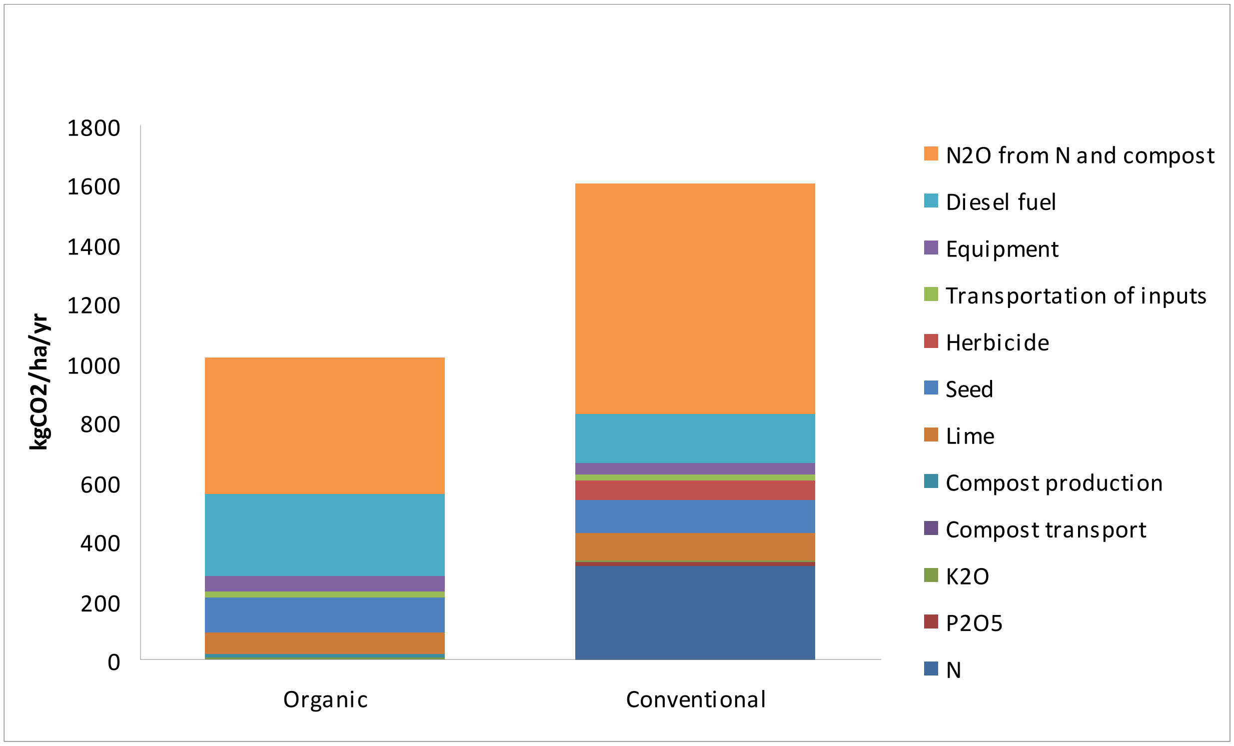

Figure 8. Organic and conventional greenhouse gas emissions from inputs.

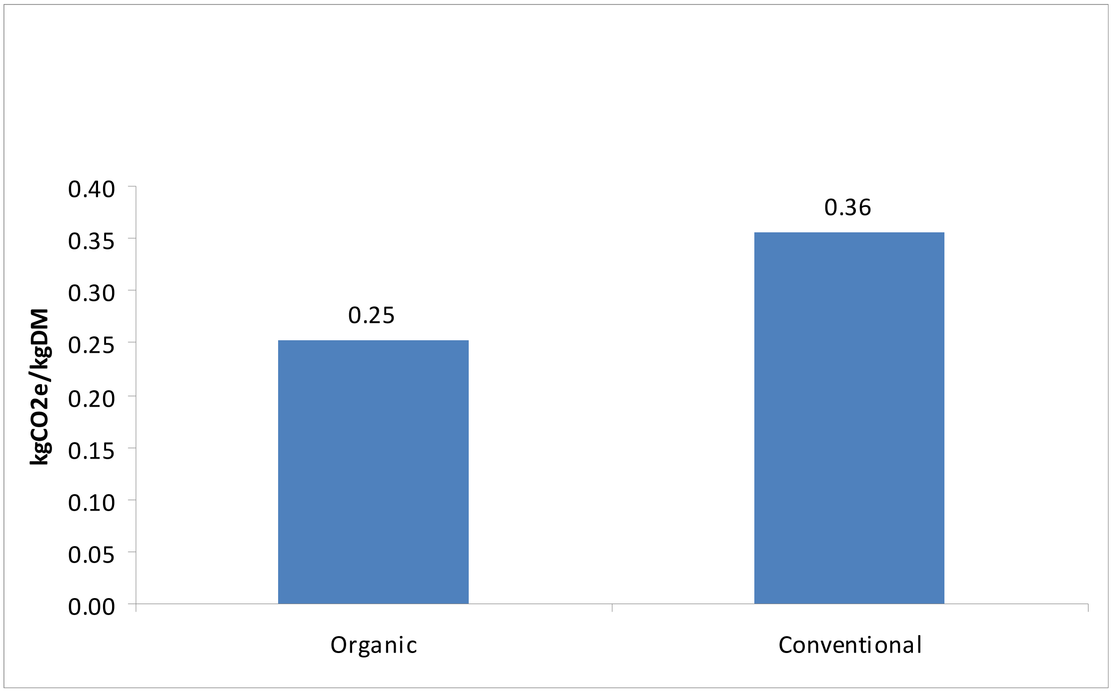

Figure 9. Organic and conventional comparison of greenhouse gas emissions inputs per crop yield.

5. Discussion

It was clear from the analysis that nitrogen has a large impact on the energy and greenhouse gas emissions. Nitrogen has a direct relationship with N_2O emissions, which in FEAT was calculated using the Intergovernmental Panel on Climate Change (IPCC) Tier 1 methodology (EPA, 2009; IPCC, 2006). This N_2O emissions calculation has a large uncertainty, ranging from 0.3 to 5% of the N added converted to N_2O-N (Crutzen, Mosier, Smith, & Winiwarter, 2008; Ogle, Del Grosso, Adler, & Parton, 2008). For the N_2O emissions from on-farm composting, the IPCC based value used in this study was 0.0355 $kgCO_2e\ kg^{-1}$ compost (using GHG_{N2O} equation in Table 2), 25% lower than in a yard waste composting emissions study (van Haaren, et al., 2010).

The biogenic CO_2, the carbon that it is cycled in the plant's lifecycle, was not accounted for. This was considered outside the analysis boundary represented in this study.

6. Conclusions

This study showed that organic cropping systems had lower energy and GHG emissions from inputs when compared to conventional tilled and no-till systems. In addition, organic systems had a lower ratio between energy/GHG and crop yield output; in other words, less energy and emissions were required in order to produce the same amount of total crop production and yield.

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