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Integrating livestock manure with a corn–soybean bioenergy cropping system improves short-term carbon sequestration rates and net global warming potential

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ABSTRACT

Carbon cycling and the global warming potential (GWP) of bioenergy cropping systems with complete biomass removal are of agronomic and environmental concern. Corn growers who plan to remove corn stover as a feedstock for the emerging cellulosic ethanol industry will benefit from carbon amendments such as manure and compost, to replace carbon removed with the corn stover. The objective of this research was to determine the effect of beef cattle feedlot manure and composted dairy manure on short-term carbon sequestration rates and net global warming potential (GWP) in a corn–soybean rotation with complete corn-stover removal. Field experiments consisting of a corn–soybean rotation with whole-plant corn harvest, were conducted near East Lansing, MI over a three-year period beginning in 2002. Compost and manure amendments raised soil carbon (C) at a level sufficient to overcome the C debt associated with manure production, manure collection and storage, land application, and post-application field emissions. The net GWP in carbon dioxide equivalents for the manure and compost amended cropping systems was -934 and $-784 \text{ gm}^{-2} \text{ y}^{-1}$, respectively, compared to $52 \text{ gm}^{-2} \text{ y}^{-1}$ for the non-manure amended synthetic fertilizer check. This work further substantiates the environmental benefits associated with renewable fuels and demonstrates that with proper management, the integration of livestock manures in biofuel cropping systems can enhance greenhouse gas (GHG) remediation.

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1. Introduction

Storage of soil organic carbon (SOC) in agricultural systems is a balance between carbon additions from non-harvested portions of crops, organic amendments, and carbon losses, primarily through organic matter decomposition and release of respired carbon dioxide (CO_2) to the atmosphere [1]. Methane (CH_4) emissions from ruminant livestock, and nitrous oxide (NO_2) and CH_4 emissions from livestock manure,

are considered major contributors to agricultural GHG emissions. Ruminant livestock can produce between 250 and 500 L of methane per day [2]. Furthermore, NO_2 and CH_4 emissions from stored manure can also be significant livestock contributions to GWP [3].

Loss of soil organic carbon is an agronomic and environmental concern in corn-stover removed bioenergy cropping systems [4]. The decline of SOC in agricultural systems combined with increased awareness of the importance of the

Abbreviations: GWP, global warming potential; GHG, greenhouse gas; P, phosphorous; POM-C, particulate organic matter carbon; PVC, polyvinyl chloride; SOC, soil organic carbon; TN, total nitrogen.

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terrestrial ecosystem in global C budgets has stimulated evaluations of land management effects on soil C dynamics and storage [5]. Past and present farming practices have resulted in loss of an estimated 4 ± 1 Pg of carbon from soils of the United States, and 78 ± 12 Pg from the world's soils, a large fraction of which ended up in the atmosphere [6]. Land use practices that may increase carbon sequestration include a switch to no-tillage (NT), greater cropping frequency [7,8], and application of organic amendments such as manure [9,10].

Despite increased oxidative losses it was estimated that approximately half of added manure carbon is retained in the soil at the end of the season [11]. Sainju et al. [12] found that poultry litter increased soil C storage compared to inorganic N fertilizer or fallow. Iazurralde et al. [13] determined that the addition of farmyard manure was a key management component leading to SOC increases. Drinkwater et al. [14] compared manure and conventional systems and found that even though both systems received equal amounts of carbon, the manure system showed a significant increase in carbon stored in soil. Rate of SOC change was directly related to carbon input from crop residues and amendments [15]. Compared with senescent-crop residues, a larger proportion of manure-derived carbon is retained in soil, probably because manure is already partly decomposed and contains a larger proportion of chemically recalcitrant organic compounds [16,17].

The positive effects of manure and compost on soil carbon fractions [18] and the negative GWP aspects associated with livestock production [2] are relatively well known. We hypothesize that the integration of livestock manures with corn-stover removed bioenergy cropping systems can increase short-term soil carbon levels sufficient to off-set carbon debt and improve net GWP relative to non-manure amended systems. The objective of this research was to determine the effects of manure and compost on short-term carbon sequestration rates and global warming potential (GWP) in a corn-soybean rotation with complete corn-stover removal.

2. Material and methods

Field experiments were conducted on the Michigan State University Agronomy Farm in East Lansing (N 42.43, W 84.28), MI over a three-year period beginning in 2002. Soil at East Lansing was a mixture of Aubeenaubee-Capac sandy loams (Fine-loamy, mixed, mesic Aeric Ochraqualfs) and Colwood-Brookston loams (Fine-loamy, mixed mesic Typic Argiaquolls and Typic Haplaquolls). The experimental design was a randomized complete block with four replications. Treatments were: beef cattle feedlot manure, dairy compost manure, and a non-manure amended synthetic fertilizer check (Fig. 1). The treatments were applied to plots in a corn-soybean rotation in two adjacent fields to facilitate entry of each crop in every year of the three-year study. Results were then combined across the two fields to provide an average for each respective treatment.

Prior to experiment establishment the site was under a corn-soybean rotation using a conventional chisel plow

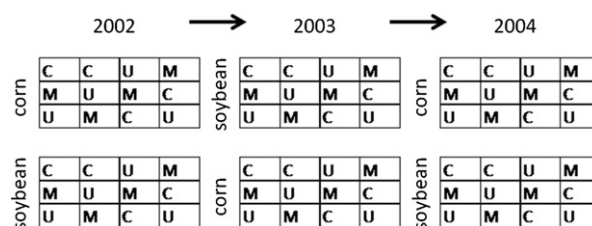


Fig. 1 – The matrix of carbon amendment field plots managed as a no-till corn-soybean rotation. C = compost; M = manure; U = untreated – no carbon amendment, fertilized with synthetic fertilizer.

tillage system. In 2001, prior to experiment establishment the site was planted to corn which was harvested as silage. No-tillage production practices were implemented for the study. Plot size was 6.1×12.2 m with 76 cm wide rows of corn or 38 cm wide rows of soybean. Planting dates, and harvest dates can be found in Table 1.

Corn was harvested with a mechanical corn forage harvester (Deere and Company, Moline, IL) which removed the whole corn plant leaving a 15 cm stem in the field. Total corn biomass dry matter (dm) yield was determined by weighing the chopped samples, and placing them in a forced-air dryer until a constant weight was observed. The dry plant material was then reweighed to calculate total dry matter. Rotational soybean was harvested for grain and soybean crop residue was left on the soil surface.

Solid beef manure and composted dairy manure were applied in the spring and fall each year of the study. Table 2 includes the date of application, rate of manure and compost application, and nutrient analyses of manure and

Table 1 – Dates of soil sampling, planting, herbicide application, and harvest.

	2002	2003	2004
		Soil sampling	
Spring 25 cm	19 Apr	21 May	9 Apr
Fall 25 cm	–	–	9 Nov
Spring 90 cm	–	22 May	19 Jun
Fall 90 cm	6 Nov	10 Nov	–
PSNT ^a	28 Jun	27 Jul	1 Jul
		Planting	
Corn & soy	23 May	22 May	13 May
		Gas sampling	
All plots		19 Apr	24 Apr
		3 May	7 Jun
		18 May	26 Jun
		1 Jun	12 Jul
		14 Jun	27 Jul
		25 Aug	11 Aug
		9 Oct	
		Harvest	
Corn	12 Sep	17 Sep	14 Sep
Soy	28 Sep	11 Oct	8 Oct
a PSNT: pre-sidedress nitrate test.			

Table 2 – Dates of manure and compost application, manure rates and analyses.

Date	Manure					Compost				
	24 Apr 02	13 Dec 02	8 Apr 03	6 Dec 03	6 Apr 04	24 Apr 02	4 Dec 02	8 Apr 03	6 Dec 03	6 Apr 04
Rate	22.0	22.5	22.5	22.5	15.7	19.5	22.5	22.5	22.5	22.5
	Mg ha ⁻¹									
	g kg ⁻¹									
C	431.0	147.2	130.5	145.2	166.1	245.5	217.0	189.0	119.1	107.5
N	3.9	5.1	3.8	2.6	6.7	7.6	9.6	13.6	7.3	6.4
P	0.8	0.7	0.9	0.8	1.0	3.7	3.8	5.2	1.7	1.7
K	4.0	3.3	3.3	3.5	3.9	7.4	6.4	5.8	7.1	6.4
Moisture	721.6	719.6	756.3	719.6	685.9	591.1	362.4	695.6	643.6	687.6
Solids	278.4	280.4	243.7	280.4	314.1	408.9	637.6	304.4	356.4	312.4
C:N ^a	110.8	28.9	34.0	55.0	24.9	32.4	22.6	13.9	16.3	16.8

a Data expressed as C:N ratio g g⁻¹.

compost. Application rates were based on estimated plant available N and surface applied with a box spreader. Reported manure and compost application rates were determined by averaging the weight of samples collected on the soil surface with a canvas tarp during spreading operations. Corn plots not receiving manure or compost amendments received sidedress N applied as liquid N solution (urea ammonium nitrate 28%) based on PSNT results at approximately the V5 stage. Soil was tested annually for P and K and no P and K fertilizer additions were made to the plots based on soil test results indicating adequate levels.

2.1. Soil sampling

Soil samples were collected using a hand soil probe in 2002 and a GeoProbe (Salina, KS 67401) slide hammer type probe in 2003 and 2004. Six soil cores 1.8 cm in diameter were collected from each plot and divided into 0–5 and 5–25 cm deep samples in the spring of 2002. Three soil cores 3.9 cm in diameter were taken per plot in the spring of 2003 and spring and fall of 2004. Samples within a plot were composited to make one bulk sample each for the 0–5 and 5–25 cm depths per plot per sampling. Soil moisture, bulk density, nitrate-nitrogen, phosphorous, SOC, TN, and particulate organic matter carbon (POM-C) content were determined from these samples. Sampling dates are in Table 1.

Soil samples were weighed before being sieved through a 4 mm screen to remove large rocks and pieces of organic material. A subsample of the sieved soil was dried at 65 °C to determine soil moisture. Bulk density was calculated by subtracting the weight of the rocks from each sample and multiplying by the percent dry soil then dividing by the total volume of soil collected minus the volume of the rocks.

A ball mill was used to finely grind a subsample of soil before analysis with a Carlo-Erba CN analyzer for determining SOC concentration. Carbon in the soil was considered 100% organic since the soil pH was below 7.0 at both locations. Soil organic carbon data is presented on a mass per unit area basis by multiplying the fraction of SOC by respective measurements of soil bulk density and depth of soil sampled.

Particulate organic matter carbon concentration was determined using a modified version of a procedure described

by Cambardella and Elliot [19]. Ten grams of soil were shaken for 15 h in a 5 g L⁻¹ solution of sodium hexametaphosphate. After shaking, the mixture was washed through a 53 µm screen with distilled water to separate the soil into two parts, mineral and particulate matter. The mineral portion was collected, dried, and ground using a mortar and pestle and then analyzed for carbon content using a Carlo-Erba CN analyzer. POM-C was calculated by subtracting the mineral associated carbon from the total carbon.

Deep core samples to a depth of 0.9 m were collected to monitor nitrate and phosphorous leaching and loading. A Giddings hydraulic probe (Ft. Collins, CO 80522) was used to extract the cores. Two cores were collected per plot and divided into four depths (0–15, 15–30, 30–60, and 60–90 cm). These samples were subjected to the same protocols as described earlier for nitrate-nitrogen and phosphorous concentration determination.

Soybean above ground residues were left on the soil surface and samples of each were analyzed to determine how much total carbon and nitrogen was being returned to the soil. Root residue contributions were estimated for corn and soybean using published values from the literature [20,21].

2.2. Gas sampling

Greenhouse gas flux from the soil was determined in 2003 and 2004 using a static chamber approach outlined by Robertson et al. [22] using semi-permanent sampling chambers placed in each plot. Chambers were polyvinyl chloride (PVC) rings 25 cm in diameter and 10 cm in height with a beveled edge on the bottom to ease placement. Chambers were inserted about 5 cm into the soil. A PVC cap with a 90° plastic elbow in the center and a 10 cm piece of plastic tubing was placed over the sampling chamber before sampling. A 10 cm wide strip of latex glued to the outside of the cap was folded down around the sampling chamber during sampling. A butyl-rubber O-ring was used to seal the latex strip tight against the chamber and to help hold the cap in place. A three-way stopcock permanently attached to the tubing allowed for mixing of the headspace atmosphere in the chamber.

A disposable 20 mL polypropylene syringe attached to the stopcock was used to draw air from the headspace

atmosphere. The syringe was drawn full with air from the chamber and then injected back to mix the chamber atmosphere; this was repeated a total of three times before collecting any samples. After mixing the chamber atmosphere, 20 mL of air was withdrawn and injected into a 10 mL container which had a 25 gauge needle placed in the rubber septum to allow for excess air to be forced out. This flushed any air trapped in the vial when capped out. This was repeated three times before removing the needle from the septum and filling the container until pressurized.

Gas samples were collected throughout the growing season in 2003, and 2004 (Table 1). Samples were collected after the cap was placed on the sampling chamber and repeated twice at 48 min intervals for a total of three times for each sampling date. Gas samples were analyzed using an HP5890 Series II gas chromatograph (Hewlett Packard, Palo Alto, CA 94304). CH₄ was analyzed with a flame ionization detector (300 °C), while N₂O was analyzed with a 63Ni electron capture detector (350 °C). Gases for both CH₄ and N₂O were separated on a Poropak Q column (1.8 m, 80/100 mesh) at 80 °C. Carrier gas for CH₄ was nitrogen, while carrier gas for N₂O was argon/methane (90/10).

Soil temperature at the 10 cm depth was measured each time a gas sample was collected and soil moisture to a depth of 15 cm was measured when the first and last samples were collected. Soil moisture was measured using a TRIME[®] TDR (MESA Systems, Medfield, MA 02052) moisture meter which measured moisture on a volume/volume basis. Three measurements were taken within 0.6 m of the canister and averaged. Height of the sampling chamber plus the cap was measured on four sides to determine the volume of the headspace. Gas flux was calculated using the following equation:

$$F = (C/T) \times ((V \times M)/(A \times V_{\text{mol}}))$$

where (C/T) is rate of change of chamber concentration of gas X, V is the chamber volume, M is the molecular weight of gas X, A is the soil area covered by the chamber, V_{mol} is the volume of a mole of gas X. This equation provides μmol of gas X min⁻¹ cm⁻² which was converted to g gas X day⁻¹ ha⁻¹.

The growing season annual flux rate was estimated by averaging the measured daily flux rates and multiplying by 180 days. The duration of the growing season was determined to be the time between the 30 y average last spring freeze (−2 °C) and first fall freeze. In this step N₂O–N and CH₄–C were converted to CO₂ equivalents using 100 y time horizon factors of 298 for N₂O and 25 for CH₄ [23]. In calculating the GWP attributable for mineralized C from the C amendments, accumulated carbon was determined by comparing fall 2004 soil C in the C amended soils with the Fall 2004 C in the non-manure amended soil. Data for each treatment were combined across the two rotations (corn–soybean–corn and soybean–corn–soybean) and carbon accumulation was determined using the following equation:

$$X \text{ kg CO}_2 \text{ m}^{-2} \text{ y}^{-1} = (((x_1 \text{ kg C m}^{-2} - x_2 \text{ kg C m}^{-2})/x_3) \times (4.4 \text{ kg CO}_2/12 \text{ kg C}))$$

where x₁ = soil C in treatment X in the fall of 2004

x₂ = soil C in the untreated in the fall of 2004

x₃ = period of accumulation in years

By using the 2004 non-manure amended soil C levels as the baseline for the C amendment treatments, the Δ soil C GWP calculation focuses on C additions attributable to the compost and manure soil amendments and standardizes temporal soil C fluctuation over the three-year study period. GWP values for agronomic inputs were obtained from West and Marland [24] and IPCC [25]. Values take into account fuel for production and transportation of seed, chemical, and fertilizer. Flux from manure production was calculated using 45 kg methane head⁻¹ y⁻¹ dairy and 3 kg methane head⁻¹ y⁻¹ beef [3] (Table 3). Consistent with local farming practices, a 90-day manure and compost storage period was assumed and storage NO₂ and CH₄ emission values were obtained from Pattey et al. [3]. Manure and compost CO₂ emissions were not included in net GWP calculations because manure carbon originates from autotrophic fixation and therefore not considered to contribute to net global warming [3]. The manure source was stockpiled beef cattle manure and the compost source was composted dairy manure. Net GWP for treatments was calculated consistent with Robertson et al. [22] using the following equation:

$$\text{Net GWP} = \Delta \text{Soil C GWP} + \text{Soil NO}_2 \text{ flux} + \text{Soil CH}_4 \text{ flux} \\ + \text{Input GHG flux}$$

All data were analyzed with the analysis of variance (ANOVA) using the PROC GLM procedure in the SAS [26]. Mean separation between variables was obtained by Tukey's Studentized Range Test. Effects were considered significant at P < 0.05.

3. Results

Total carbon input over three growing seasons was greatest with manure (Table 4). Manure application resulted in 21.6 Mg ha⁻¹ of carbon being added to the soil surface over the three years of the study. The majority of that carbon was added in 2002 (59%) when beef feedlot manure with sawdust bedding was used (43% C). Compost treatments added 19.0 Mg ha⁻¹ of carbon. Additionally, since the carbon amendment application rate was based on plant available N, the applications did not affect measured corn biomass or estimated ethanol yield (Table 5).

Soil temperature was significantly affected by soil amendment in 2003 and 2004 though all treatments were within 2 °C of each other at every sampling (data not shown). When soil temperature did vary, compost and manure generally had lower soil temperatures and higher soil moisture levels than the no amendment treatment check. The lower soil temperatures of the amended treatments were probably due to the insulating affect of the surface applied manure and compost material. The application of the organic material produced a buffer zone between the soil surface and the sun protecting the soil from direct sunlight therefore decreasing the ability of the sunlight to heat the soil. It is possible that lower soil temperatures in the amended treatments may have slowed mineralization of organic matter. This is consistent with the findings of Kravchenko and Thelen [27] who reported lower spring soil temperature and higher soil moisture levels with manure and compost soil amendments in no-till cropping systems.

Table 3 – Average annual application rate, cattle equivalents, and manure production global warming potential for cattle enteric fermentation, land application machinery, and 90-day storage period for manure and compost.

Manure source	Application rate	Cattle equivalents	Enteric fermentation ^a	Land application ^b	90-day Storage ^c
	kg ha ⁻¹	Head ha ⁻¹		g CO ₂ equiv m ²	
Solid beef manure	9714.3	8.6	65	0.5	73.4
Dairy compost	14730.3	8.0	899	0.5	304.8

a Cattle enteric fermentation was calculated 45 kg methane head⁻¹ y⁻¹ dairy and 3 kg methane head⁻¹ y⁻¹ beef.

b Agricultural input GWP values obtained from West and Marland [24] and IPCC [25].

c Consistent with local farming practices, a 90-day manure and compost storage period was assumed and storage NO₂ and CH₄ emission values were obtained from Pattey et al. [3].

N₂O–N was not affected by soil amendment (Table 6). Nitrification and denitrification of N that is added to the soil to sustain crop productivity are responsible for the majority of N₂O emissions [28]. Since the manure and compost amendments, as well as the synthetic fertilizer used in the non-amended treatment were applied to the soil based on plant available nitrogen being the rate limiting factor, it could be expected that N₂O–N emissions would not vary significantly.

CH₄–C emissions were influenced by soil amendment. Agricultural soils generally act as a sink for CH₄–C except under anaerobic conditions. Therefore it is interesting that manure resulted in a net CH₄ emission of 0.07 g CO₂ m⁻² y⁻¹ equiv compared to compost and the non-amended treatment which served as a sink for atmospheric CH₄ at a measured rate of –0.32 and –0.93 g CO₂ m⁻² y⁻¹ equiv, respectively. The observed 0.07 g CH₄–C emission associated with the manure treatment is small and therefore could possibly be a measurement artifact. Soil moisture was 27–29% volume:volume (data not shown) so anaerobic conditions were not present to account for the single occurrence of CH₄–C emissions with the manure treatment.

Calculation of Δ soil carbon GWP was made by subtracting the baseline soil carbon content from the ending soil carbon

content, dividing by the period of accumulation, and converting the amount of carbon into its equivalent mass as CO₂ equivalents. The manure and compost soil amendments improved Δ soil carbon GWP levels in the soil profile (Table 6) as indicated by a negative GWP value. Compost decreased Δ soil carbon GWP (–2064 g CO₂–C m⁻² y⁻¹) more than manure (–1175 g CO₂–C m⁻² y⁻¹). Both manure and compost decreased Δ soil carbon GWP more than the non-manure amended check (0.0 g CO₂–C m⁻² y⁻¹). Compost and manure resulted in similar net GWP mitigation potentials of –784 and –934 g equiv CO₂ m⁻² y⁻¹, respectively. However, the non-manure amended corn-stover removed cropping systems had a net positive GWP of 52 g CO₂ m⁻² y⁻¹.

4. Discussion

Manure and compost additions, particularly in no-tillage systems can beneficially or adversely affect early season plant growth by influencing nutrient levels, soil temperature, and soil moisture [27]. Although our study focused on short-term changes in SOC using manure, the results are consistent with Sainju et al. [12] who found that long-term applications of poultry litter increased soil C storage. Their work did not directly evaluate the manure effect on net GWP but the authors suggested that proper manure integration with cropping systems would sequester C, off-set atmospheric CO₂ levels, and improve soil and environmental quality.

The Δ soil carbon GWP in the no-till cropping systems increased significantly ($P < 0.05$) more with compost compared to manure and the non-amended check. This occurred even though the cumulative carbon loading rate (Table 4) for the compost treatment was slightly less than that of the manure treatment. This is consistent with Eghball [29], who reported a greater fraction of carbon remaining in the soil

Table 4 – Carbon input from manure and compost amendments.

C source	2002	2003	2004	Total
<i>Manure & compost^a</i>				
				Mg ha ⁻¹
Manure	12.8	6.2	2.6	21.6
Compost	9.7	6.9	2.4	19.0
Untreated	–	–	–	–
<i>Estimated crop residue carbon^b</i>				
<i>corn and (soybean)</i>				
Manure	0.9 (1.7)	0.7 (1.8)	0.7 (1.6)	2.3 (5.1)
Compost	1.0 (1.8)	0.9 (2.0)	0.8 (1.6)	2.7 (5.4)
Untreated	1.1 (1.5)	0.9 (2.2)	0.7 (2.2)	2.7 (5.3)
<i>All sources</i>				
Manure	13.7 (14.5)	6.9 (8.0)	3.3 (4.2)	23.9 (26.7)
Compost	10.7 (11.5)	7.8 (8.9)	3.2 (4.0)	21.7 (24.4)
Untreated	1.1 (1.5)	0.9 (2.2)	0.7 (2.2)	2.7 (5.9)

a Manure and compost C contribution calculated based on application rate and manure analyses.

b Root residue contributions were estimated for corn and soybean using published values from the literature [20,21]. Soybean estimates include measured above ground soybean residue carbon returned to soil.

Table 5 – Whole-plant corn biomass and estimated (ethanol) yields removed from the cropping system as affected by manure and compost amendment.

Treatment	2002	2003	2004
			Mg ha ⁻¹ (L ha ⁻¹)
Manure	13.6 (4080)	10.5 (3150)	14.1 (4230)
Compost	14.1 (4230)	13.1 (3930)	15.6 (4680)
Untreated	16.2 (4860)	12.9 (3870)	14.3 (4290)
	NS	NS	NS

Table 6 – Soil carbon global warming potential (GWP), soil greenhouse gas (GHG) flux, input GHG flux, and net GWP.

	Δ Soil carbon GWP ^{a,b}	Soil NO ₂ flux ^c	Soil CH ₄ flux ^c	Input GHG flux ^d	Net GWP ^e
Soil amendment			g CO ₂ m ⁻² y ⁻¹		
Manure	-1175	93.3	0.1	148	-934
Compost	-2064	65.9	-0.3	1214	-784
Untreated	0	44.0	-0.9	9	52
HSD	640	NS	0.7	-	642

HSD: minimum significant difference (0.05) from Tukey's test.
a Δ soil GWP is the potential for soil sequestration of carbon with that specific treatment compared to an untreated check.
b Negative values indicate mitigation of GHG.
c Total annual flux of GHG from the soil surface in CO₂ equivalents.
d Average annual flux of GHG from crop inputs, manure and compost production plus 90-day manure and compost storage.
e Net annual GWP mitigation potential (Soil C GWP + Soil NO₂ flux + Soil CH₄ flux + Input GHG flux).

after compost application compared to manure. However, the findings disagree with work done by Rochette and Gregorich [11] who found that stockpiled manure increased SOC more than rotted (partially composted) manure when incorporated to a depth of 20 cm. The greater potential for soil carbon based GWP mitigation with compost is due to the more recalcitrant nature of compost derived carbon compared to manure [29].

Average annual input GHG values accounted for fuel for production, transportation, and application of seed, chemical, and fertilizer. Methane flux from livestock was included in the input calculations for treatments including manure and compost. Consistent with local farming practices, a 90-day manure and compost storage period was assumed. As shown in Table 4, the 90-day manure storage process accounts for a significant amount of the GWP associated with the manure and compost amendments. This result, taken out of context, suggests that manure storage should be eliminated or minimized. However, other environmental issues, including surface runoff and soil compaction are managed by temporarily storing manure and only applying when field conditions

are optimal for reducing these other potential negative environmental impacts. The significantly higher input GHG flux rate from compost is due to several factors including: the source being dairy manure and higher CH₄ enteric fermentation losses associated with dairy rations relative to beef rations; a greater quantity of manure is needed for composting due to manure respiration loss during the compost process; and, the resulting increased N₂O loss during the composting procedure adds directly to the GHG flux and results in greater quantities of material required when basing field application rates on plant available N [3].

Compost and manure amendments made to the soil resulted in a net GWP of -784 and -934 g equiv CO₂ m⁻² y⁻¹ respectively. These results demonstrate that integrating livestock wastes, as manure or compost, can significantly reduce the net GWP of crop systems. Additionally, overall GWP is further improved when crops harvested from the system are used as biofuel feedstock to displace fossil fuels. Fig. 2, depicts the potential increased GWP advantages associated with the manure and compost amended biofuel cropping systems based on the displacement of fossil fuels with the biofuel generated from each crop system. The possible GWP improvement due to the displacement of gasoline is depicted by the lower, open bars paired with the respective net GWP of the manure, compost, and synthetically fertilized cropping systems. The additive affect of integrating livestock waste into the cropping system, and the utilization of the crops as biofuel feedstock to displace fossil fuels is demonstrated by the total bar length for each respective cropping system. For example, the manure amended cropping system yielded an average 3.82 m³ ha⁻¹ of ethanol which effectively displaces 2.67 m³ of gasoline on the open market. The GWP of that volume of gasoline is 6222 kg CO₂, while the manure amended cropping system, on a ha basis, had a net GWP of -9340 kg equiv CO₂ m⁻² y⁻¹. Collectively, the net GWP of the crop system and the resulting gasoline displacement is -15,562 kg ha⁻¹ y⁻¹.

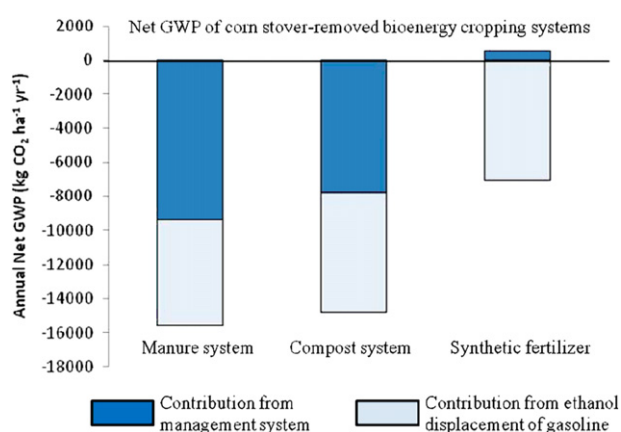


Fig. 2 – Net global warming potential (GWP) of corn cellulosic biomass biofuel cropping systems (kg of CO₂ equiv ha⁻¹ y⁻¹) as affected by manure, compost, or synthetic fertilizer amendments. Annual crop system net GWP data represents annual average of a corn-soy rotation; ethanol yield calculated at 300 L Mg⁻¹ corn biomass. Gasoline displaced was calculated as 0.7× the ethanol produced by each respective cropping system.

5. Conclusions

The integration of livestock manures in corn-stover removed bioenergy cropping systems increased short-term soil carbon levels sufficient to off-set the system carbon debt and improve net GWP relative to non-manure amended, synthetically

fertilized systems. This work further substantiates the environmental benefits associated with renewable fuels and demonstrates that with proper management, the integration of livestock manures in biofuel cropping systems can enhance GHG remediation.

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