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Environmental and economic trade-offs of using composted or stockpiled manure as partial substitute for synthetic fertilizer

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Abstract

Manure generated from livestock production could represent an important source of plant nutrients in substitution of synthetic fertilizer. To evaluate the sustainability of partially substituting synthetic fertilizer with soil organic amendments (OAs) in horticulture, an economic and greenhouse gas (GHG) budget was developed. The boundary for analysis included manure processing (stockpiling vs. composting) and transport and spreading of manure and compost (feedlot and chicken) in intensively cultivated horticultural fields. The OA field application rates were calculated based on the nitrogen supplied by OAs. The GHG budget based on directly measured emissions indicates that the application of composted manure, in combination with reduced fertilizer rate, was always superior to stockpiled manures. Compost treatments showed from 9 to 90% less GHG emissions than stockpiled manure treatments. However, higher costs associated with the purchase and transport of composted manure (three times higher) generated a greater economic burden compared with stockpiled manure and synthetic fertilizer application. The plant nutrient replacement value of the OAs was considered only for the first year of application, and if long-term nutrient release from OAs is taken into account, additional savings are possible. Because the income from soil carbon sequestration initiatives in response to OA application is unlikely to bridge this financial gap, particularly in the short term, this study proposes that future policy should develop methodologies for avoided GHG emissions from OA application. The combined income from soil carbon sequestration and potentially avoided GHG initiatives could incentivize farmers to adopt OAs as a substitute for synthetic fertilizers, thereby promoting more sustainable farming practices.

Abbreviations: CCM, composted chicken manure; CFM, composted beef feedlot manure; CM, chicken manure; dw, dry weight; EF, emission factor; FM, beef feedlot manure; fw, fresh weight; GHG, greenhouse gas; GREET, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation; IPCC, Intergovernmental Panel on Climate Change; OA, organic amendment; PAN, plant available nitrogen.

1 | INTRODUCTION

Before the introduction of synthetic fertilizer, the application of organic amendments (OAs) such as animal manures to agricultural soils was the traditional way of fertilizing crops because between 55 and 95% of the nitrogen (N) and about 70% of the phosphorus (P) ingested by livestock are excreted through urine or feces (Menzi et al., 2010). The intensification of global meat consumption has resulted in an exponential increase in manure production, contributing to the accumulation of nutrient-rich manure around areas dedicated to livestock feeding operations (Spiegal et al., 2020). These manure-nutrient rich "hotspots" pose several environmental challenges, such as the emissions of greenhouse gases (GHGs) and nutrients leaching to groundwater and their subsequent movement into rivers and estuaries, causing eutrophication of the terrestrial water body ecosystem (Mottet et al., 2017). Relocating surplus manure nutrients from nutrient hotspots to nutrient-deficit cropland can alleviate the environmental burden associated with livestock production operations while reducing the need for fertilizer imports (Powers et al., 2019; Spiegal et al., 2020). Nevertheless, sustainable relocation and land application of OAs require several economic and environmental considerations.

There are indisputable benefits of OA application as a means of sustaining soil physical and chemical fertility (Diacono & Montemurro, 2010). However, these benefits are often associated with application rates many times larger than what is necessary to supplement synthetic fertilizer (Quilty & Cattle, 2011). The over-application of OAs might exacerbate soil nitrous oxide (N_2O), a potent GHG, due to soil inorganic N levels exceeding crop N demand (De Rosa et al., 2018; VanderZaag et al., 2011). The careful consideration of OA types and application rates is crucial to maximizing its benefits while minimizing the associated environmental impacts. De Rosa et al. (2018) compared the application of composted and stockpiled manure and demonstrated that the balanced application of composted manure with reduced synthetic fertilizer to match crop needs reduces soil N_2O. This reduction in GHG emissions was attributed to the higher stability of organic matter, the larger content of recalcitrant material, and the lower mineral N availability for nitrifying and denitrifying microorganisms in composted rather than raw manures.

The composting process has also been demonstrated to reduce pathogens and weed seeds and to reduce material weight and volume (Eghball, 2000) and thus is a preferred way to improve export potential for dry feedlot manure (Spiegal et al., 2020). However, manure composting also emits GHGs, and estimation of these emissions is currently based on default emission factors (EFs) recommended by the Intergovernmental Panel on Climate Change (IPCC). The default EFs for composting have been largely questioned, and literature values vary widely (Ba et al., 2020) from 0.004 g CH_4–C kg^{-1} dry matter and 0.01 g N_2O–N kg^{-1} total N (Biala et al., 2016) to 0.85 g CH_4–C kg^{-1} dry matter and 10.40 g N_2O–N kg total N (Fillingham et al., 2017). Therefore, although there are numerous benefits to OA application, it is still uncertain whether the life cycle GHG emissions generated from transport (especially long-haul) and the composting process offset the reduction in soil GHGs observed on application of composted OAs.

Core Ideas

- Soil organic amendments are a valid substitute for synthetic fertilizer.
- The use of compost rather than manure reduces GHG emissions from the manure supply chain.
- The reduction of fertilizer should be considered as an environmental credit.

In addition to the environmental impact, the development of sustainable farming systems should ensure the economic viability of OA application because this will ultimately determine the adoption of this practice by farmers. Farmers would only purchase OAs as a substitute or in combination with synthetic fertilizer if the total cost associated with the use of OAs is lower than or comparable to that of synthetic fertilizer. Although the substitution of synthetic fertilizers with OAs could reduce the environmental impact associated with the industrial production of synthetic fertilizer, in circumstances where the economic revenue derived from OAs is lower than synthetic fertilizer, economic support may be needed to incentivize adoption. However, the economic revenue derived solely from the nutrient replacement value of OAs is difficult to quantify because it depends on geographical context and local regulation policies (Leip et al., 2019). Therefore, the environmental and economic costs and benefits of the use of OAs as a substitute for synthetic fertilizer cannot be understood unless the entire supply chain is considered.

The objective of this study was to quantify the environmental and economic trade-offs associated with using composted versus stockpiled manure as a partial substitute for synthetic fertilizer. Greenhouse gas and economic budgets were developed for an OA supply chain case study including measurements of total GHG emissions and economic cost-benefit generated from the manure processing operations (i.e., composting and stockpiling), transport to the field, and manure spreading in a horticultural crop rotation.

2 | MATERIALS AND METHODS

To evaluate the economic and environmental trade-offs of applying composted or stockpiled manures to agricultural soils, total GHG emissions along with the associated costs were estimated from the composting and stockpiling process, transport of the OA from processing site to field site, and field application.

2.1 | Horticultural field experiment

In this case study, the intensively cultivated agricultural soil for vegetable crop production was chosen as potentially representing the upper end of field GHG emissions (Rezaei Rashti et al., 2015). Intensively cultivated agricultural soils for vegetable crop production are characterized by high N-fertilizer application rates often combined with OA applications, leading to annual total N application rates ranging from 220 to 1,145 kg N ha^{-1} yr^{-1} (De Rosa et al., 2018; Porter et al., 2017; Scheer et al., 2017).

The details of the experimental design and plant nutrients (N, P, and K) management strategies can be found in De Rosa et al. (2016). Briefly, a field experiment was conducted from September 2013 to September 2014 at Gatton Research Station in the Lockyer Valley, a major vegetable producing region in southeast Queensland, Australia (27˚32′56″ S, 152˚19′39″ E; 100 m asl). The crop rotation under investigation comprised a succession of three vegetable crops: green beans (*Phaseolus vulgaris* L.), broccoli (*Brassica oleracea* var. *italica*) and lettuce (*Lactuca sativa* L.). Sorghum [*Sorghum bicolor* (L.) Moench] was used as a cover crop to reduce N losses during the summer fallow period between green beans and broccoli.

Ten fertilizer treatments were arranged in a randomized block design with four replicates (1.5 m by 10 m with 1.5-m buffer):

1. A conventional N-fertilizer rate (CONV, 310 kg of N ha^{-1}) and 65 kg of P ha^{-1} and 178 kg of K ha^{-1} for the entire rotation based on local farm management.
2. Zero N input treatment (0N) was used to account for background soil GHG emissions.

Eight treatments of OA were derived from the factorial combination between (a) four organic amendments: conventionally stockpiled beef feedlot manure (FM) and chicken manure (CM) and aerated turned composted chicken manure (CCM) and composted beef feedlot manure (CFM) and (b) two levels of synthetic N-fertilizer: reduced (+N_{Rd}) and a conventional (+N_{CONV}) N-fertilizer rate. The factorial combination between OA and different N-fertilizer rates included:

3. Composted chicken manure plus conventional N-fertilizer rate (CCM+N_{CONV}).
4. Composted chicken manure plus reduced N-fertilizer rate (CCM+N_{Rd}).
5. Stockpiled chicken manure plus conventional N-fertilizer rate (CM+N_{CONV}).
6. Stockpiled chicken manure plus reduced N-fertilizer rate (CM+N_{Rd}).
7. Composted feedlot manure plus conventional N-fertilizer rate (CFM+N_{CONV}).
8. Composted feedlot manure plus reduced N-fertilizer rate (CFM+N_{Rd}).
9. Stockpiled feedlot manure plus conventional N-fertilizer rate (FM+N_{CONV}).
10. Stockpiled feedlot manure plus reduced N-fertilizer rate (FM+N_{Rd}).

The OAs were added at the start of the crop cycle on 2 Sept. 2013 and incorporated with a rotary hoe to a depth of 0.2 m. The OA application rates were determined to match the basal N-fertilizer application rate in the CONV treatment (35 kg N ha^{-1}) considering the fraction of plant available N (PAN, NO_3^- + NH_4^+) content in the OAs. The amount of OA applied and the respective concentrations of N, P, and K provided at application are reported in Table 1.

The +N_{Rd} N-fertilizer rate was calculated by subtracting the estimated PAN delivered by the OA from the CONV N-fertilizer application rate. The PAN delivered by OA was estimated by multiplying the amount of organic N supplied by OA with mineralization rate coefficients (Table 1) taken from the literature (Eghball et al., 2002; Hartz et al., 2000) divided into quartiles (3 mo) for the entire duration of the crop rotation using Equation 2 described in De Rosa et al. (2017). The application of OAs provided 29, 278, 299, and 157 kg P ha^{-1} for CM, CCM, FM, and CFM, respectively, and 91, 431, 995, and 498 kg K ha^{-1} for CM, CCM, FM, and CFM, respectively (Table 1). For the P and K fertilization strategies, only the CONV and 0N treatments received supplemental P and K synthetic fertilizer (67 kg P ha^{-1} and 179 kg K ha^{-1}), whereas OA treatments did not receive any P and K synthetic fertilizer supplements.

The yearly amount of fertilizer and estimated N available from OAs for the crop rotation are listed in Table 2.

Plots were irrigated at least once a week using an overhead sprinkler irrigation system following standard farming practice. Crop residues were incorporated at the end of each crop growing phase with a rotary hoe to 0.2 m depth. Permanent crop beds (1.5 m by 10 m with 1.5-m buffer) that accommodated two plant rows were reformed following the incorporation of crop residues.

2.1.1 | Plant and soil analysis

At each harvest, crop yield and total biomass production were measured by harvesting all plants (15 m^2) within each experimental plot. Representative plant samples (four per plot) were

TABLE 1 Composition and application rates of chicken (CM) and feedlot (FM) manures and composted chicken (CCM) and feedlot (CFM) manures on dry weight basis at Gatton Research Facility, Queensland, Australia (2013–2014)

	Chicken		Feedlot	
	CM	**CCM**	**FM**	**CFM**
Composition				
H_2O, %	60	34	16	30
Organic C, %	24.2	23	20	17
Total N, %	7.2	1.9	1.9	2.7
C/N ratio	3.3	12	10.5	6.3
NO_3^-–N, mg kg^{-1}	115	93.9	87	32
NH_4^+–N, mg kg^{-1}	2,4845	2,819	829	1,403
P, %	2.4	2.2	0.85	0.9
K, %	6	3.5	2.9	2.9
S, %	0.54	0.64	0.65	0.6
Field application, Sept. 2013				
OA application, t dry wt. ha^{-1}	1.4	12.5	35.3	17.5
Total N, kg N ha^{-1}	102	240	699	466
Organic N, kg N ha^{-1}	67	205	660	430
PAN, kg N ha^{-1}	35	35	35	35
P, kg P ha^{-1}	29	278	299	157
K, kg K ha^{-1}	91	431	995	498
S, kg S ha^{-1}	8	79	230	106
Organic C, kg C ha^{-1}	340	2,884	7,059	2,882
Annual mineralized organic N				
MR, %	33	12	23	9
Mineralized PAN, kg N ha^{-1} yr^{-1}	22	25	157	39

Note. MR, estimated annual mineralization rate (De Rosa et al., 2017; Eghball, 2000; Hartz et al., 2000); OA, organic amendment; PAN, plant available N (NO_3^- + NH_4^+).

oven-dried for 24–48 h at 70 ˚C and subsequently ground and analyzed for total N and C content using a Leco Trumac CNS Analyzer (LECO Corp.). Soil organic C (SOC) was measured from each plot prior to OA application in September 2013 and at the end of the field experiment in September 2014 by collecting four subsamples of soil per plot (0–0.15 m) and analyzed using Leco Trumac CNS Analyzer.

2.1.2 | GHG measurements from the field experiment

For the horticultural field experiment, high temporal resolution measurements of soil N_2O and CH_4 fluxes from each experimental plot were collected with an automated chamber sampling system as described in De Rosa et al. (2016) from the treatments that received CM, CCM, CONV, and 0N. Nitrous oxide and CH_4 emissions were also measured from the treatments that received FM and CFM, using the manual closed chamber method.

The automated chamber sampling system used in the horticultural field experiment consists of transparent acrylic static chambers (0.5 by 0.5 by 0.15 m) fixed on stainless steel bases inserted 0.1 m into the soil and equipped with pneumatically operated lids. The chambers were linked to a computerized sampling unit and an in situ gas chromatograph (SRI GC 8610C) equipped with a ^{63}Ni electron capture detector for N_2O, a flame ionization detector for CH_4, and an infrared gas analyzer (LI-820, LI-COR) for CO_2. During closure (1 h), each chamber was sampled every 15 min with a known calibration standard every fifth measurement, obtaining eight fluxes per day from each chamber. Chambers were opened during irrigation events, and a tipping bucket rain gauge connected to the system facilitated the automatic opening of the lids to ensure rainfall entered the chambers.

In the FM and CFM treatments, the manual gas samples were taken between 10 AM and 12 PM every 2–3 d during the first 2 wk after fertilization and incorporation of OAs and crop residues and weekly for the rest of the time. The polyethylene manual chambers were the same dimensions as the automated chambers. Chamber headspace gas samples (20 ml) were collected 0, 30, and 60 min after closure by connecting a syringe to a two-way Luer lock tap installed in the lid of the chamber and then injected into a pre-evacuated 12-ml glass vial (Friedl et al., 2017; Scheer et al., 2017). Manual gas samples were analyzed for N_2O and CH_4 by laboratory-based gas chromatography (GC-2014, Shimadzu). The N_2O and CH_4 fluxes from the automated chambers were calculated from the slope of the linear concentration increase of the four and three measurements for the automated and manual chambers, respectively, taken over the 60-min chamber closure time (Scheer et al., 2014). Mean daily fluxes from the automated system (g N_2O–N ha^{-1} d^{-1} and g CH_4–C ha^{-1} d^{-1}) were obtained by averaging sub-daily fluxes over a 24-h period from each chamber. Data gaps were filled using linear interpolation by chamber across the missing day (Dorich et al., 2020). Cumulative N_2O fluxes (g N_2O–N ha^{-1} and g CH_4–C ha^{-1}) were calculated by summing the daily average of each individual chamber over the 1-yr crop rotation.

Two different approaches were used to calculate the annual N_2O EFs from the horticultural field experiment for the treatments that received OAs; both used 0N treatment to correct for soil background emissions. The first approach (EF) took into account the yearly total N applied with OAs plus N-fertilizer following the Tier 1 methodology of the IPCC (Kroeze et al., 1997); the second approach (EF_{OA}), proposed by De Rosa et al. (2016), only accounted for the estimated N mineralized from OA (cumulative PAN) plus the N-fertilizer (Table 2). The Benjamini and Hochberg procedure (Benjamini & Hochberg, 1995) was performed to assess significant

TABLE 2 Annual rate of N application, calculated by summing the N-fertilizer and N supplied from organic amendments over the entire crop cycle at Gatton Research Facility (2013–2014)

Treatment[a]	N-fertilizer	N_{OA}[b]	PAN[c]	N-fertilizer + N_{OA}	N-fertilizer + PAN	Fertilizer reduction in +Rd from CONV
	kg N ha^{-1}					%
CONV	310	–	–	310	310	
CM+N_{CONV}	310	102	57	412	367	
CM+N_{Rd}	252	102	57	355	310	19
CCM+N_{CONV}	310	240	60	550	370	
CCM+N_{Rd}	249	240	60	490	310	20
FM+N_{CONV}	310	698	192	1,008	502	
FM+N_{Rd}	118	698	192	816	310	62
CFM+N_{CONV}	310	466	74	776	384	
CFM+N_{Rd}	236	466	74	702	310	24

[a]CCM, composted chicken manure; CFM, composted feedlot manure; CM, stockpiled chicken manure; CONV, conventional N, P, and K application rate; FM, stockpiled feedlot manure; +N_{CONV}, conventional N fertilizer rate; +N_{Rd} reduced N fertilizer rate.

[b]Total N supplied with the application of organic amendments

[c]Mineral N supplied with the application of organic amendments as the sum of the mineral N content at the time of organic amendments application (September 2013) and the estimated N mineralized over time.

differences ($p < .05$) in cumulative N_2O and CH_4 emissions and on EF.

2.2 | Composting and stockpiling experiments

The GHG measurements during stockpiling and composting of cattle feedlot manure and layer chicken manure were taken at two separate facilities near Toowoomba, Queensland, Australia (27˚34′04.6″ S, 151˚56′10.1″ E). Manure processing at the two sites was carried out as follows.

2.2.1 | Beef cattle feedlot

The manure stockpile (866 t fresh weight [fw]) was established by compacting manure collected from feed pens with a front-end loader as is typical practice for the industry. The stockpile remained untouched for the duration of the GHG measuring period (153 d). Manure (211 t fw) was also composted for 104 d, using windrow composting turned with a front-end loader 30, 60, and 90 d after establishment. Water was supplied with a hand-held hose each time the windrow was turned.

2.2.2 | Layer chicken manure composting facility

The manure stockpile (78 t fw) was established by tipping manure from the delivery truck, which then remained untouched for the duration of the monitoring period (154 d). Manure was also composted for 161 d after blending it with sawdust at a 4:1 (v/v) ratio, which equates to approximately 10:1 on a weight basis. The windrow comprised around 201 t (fw) manure and 20.6 t (fw) sawdust and was turned frequently (14, 25, 33, 40, 57, 71, 90, 117, and 124 d after windrow establishment) with a self-propelled straddle windrow turner. Water was supplied via the windrow turner and added as needed.

2.2.3 | GHG measurements during the composting and stockpiling experiments

Five round greenhouse gas sampling chambers (diameter, 0.235 m; height, 0.3 m with 0.2 m headspace) were placed equidistant on each of the stockpiles and the windrows. Gas sampling occurred twice per week for the first 6 wk of the trial and then at weekly intervals. Sampling from each chamber involved taking three samples at 2-min intervals, starting 2 min after the lid of the chamber was closed. Samples were drawn from the chamber via a three-way valve by extracting 20 ml of gas with a syringe and injecting 20 ml into a 12-ml evacuated vial. Samples were analyzed for N_2O and CH_4 at the Queensland University of Technology laboratory using a Shimadzu GC-2014 gas chromatograph. Fluxes were calculated as described for the horticultural field experiment. The emissions for periods between sampling events were estimated by means of linear interpolation, providing daily and cumulated emission values for each chamber for the entire trial period. Total emissions were calculated by multiplying emissions per gas chamber surface area (0.055 m^2) by the flat top surface area of stockpiles and windrows. Windrows had a trapezoidal shape, with the top surface area being measured after establishment and each turning. Emissions were measured only from the flat top surface area because it was shown that 100% of CH_4 and 91% of N_2O is emitted via the top of large windrows (Andersen et al., 2010). Emissions per ton of manure and composting feedstock (chicken manure) were calculated as cumulative emissions in relation to the mass of manure used for establishing the stockpiles and windrows. Estimated carbon losses during stockpiling (feedlot manure: 2.4%; chicken manure: 0.4%) and composting (feedlot manure: 34.0%; chicken manure: 39.2%) were used to convert input-based (per t dry weight [dw] manure) to output-based (per t dw manure or compost applied) emissions.

2.3 | Calculation of economic and GHG budget for OA treatments

The economic budget of different OA treatments was calculated based on the local purchase price of OAs and synthetic fertilizers (i.e., N, P, and K) plus the costs associated with the transport of the materials to farm (110 km traveling distance from manure-nutrient hotspots to nutrient-deficit cropland) and the handling and spreading of OAs and synthetic fertilizers on field. The purchase prices of CM and CCM used in our analysis were US\$18.5 and US\$54.6 fw t^{-1}; those for FM and CFM were US\$8.9 and US\$38.6 fw t^{-1}, respectively. The purchase prices of synthetic fertilizers were considered on an element basis, including US\$1.4 kg N, US\$6.2 kg^{-1} P, and US\$2.4 kg^{-1} K. For both OAs and fertilizers, we used a transport cost of US\$0.11 t^{-1} km^{-1} and an application (spreading) cost of US\$3.1 t^{-1}. The information regarding prices of products (OAs and fertilizers) and service (transport and spreading) were obtained from local producer and national consultants.

The GHG emission budget used a cradle-to-field boundary and considered the emissions from different sources, including the production, transport, and field spreading of OAs and synthetic fertilizers and soil GHG emissions from the horticultural field over a 1-yr timeframe. The emissions associated with the production of OAs (i.e., stockpiling and composting processes) and soil emissions were captured with the chamber measurements described in Sections 2.2.1 and 2.2.2. Because CO_2 emissions from biological systems are considered to rapidly cycle and occur anyway in natural systems during the breakdown of organic residues, these biogenic emissions are considered to have no net global warming effect (Christensen et al., 2009). Due to only a portion of the OAs organic C being mineralized during the first-year application, the possible changes in soil C content observed in the OAs treatments are considered transient and therefore are not included in the environmental budget.

Methane and N_2O emission values were converted to carbon dioxide equivalents (CO_2-eq) using global warming potential factors of 28 for CH_4 and 265 for N_2O (IPCC, 2019).

To calculate the GHG emissions associated with the production of synthetic fertilizer as well as the transport and application of OAs and fertilizers, we used the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (GREET) (Argonne National Laboratory, 2019; Wang et al., 2020). The GREET model's default emission coefficients were used for the manufacturing and for the transport and distribution of fertilizers, which are 3.87, 0.65, and 0.53 kg CO_2-eq kg^{-1} of N, P, and K, respectively. An emission of 4.5 kg CO_2-eq ha^{-1} was used for field spreading of fertilizers, as reported by Hanna (2005).

For our case study, composts and manures were transported directly from the processing facilities to the study sites for application. We assumed these organic materials were transported using an industrial truck with a capacity of 32 tons per load. The fuel consumption of this truck was estimated under different road conditions (i.e., urban vs. rural) for a round trip from the manufacturing facility to the application site (loaded) and nonbackloading return (unloaded) (ROU-UNSW, 2006). The transport distances in urban and rural areas were 10 and 100 km, respectively. Composts and manures were applied to the field using an OA spreader with a fuel consumption rate of 23.5 L h^{-1} fuel and a handling rate of 200 t d^{-1} (~9 working hours) (ROU-UNSW, 2006). The fuel consumptions were converted to GHG emissions using GREET's coefficient of 3,220 g CO_2-eq L^{-1} of diesel combusted (Argonne National Laboratory, 2019). These calculations resulted in emission rates of 3.3 kg CO_2-eq t^{-1} km^{-1} and 3.4 kg CO_2-eq t^{-1} for OA transport to field and on-field spreading, respectively.

3 | RESULTS AND DISCUSSION

3.1 | Economic budget

The application of OAs in combination with either the reduced fertilizer rate (+N_{Rd}) and the conventional N fertilizer rate (+N_{CONV}) showed no significant positive or negative effect on crop production in comparison to CONV (Table 3). Total yields were 4.1 ± 0.5 to 5.1 ± 0.8 t dw ha^{-1} for FM+N_{Rd} and CFM+N_{CONV}, respectively. This yield level was achieved despite reducing synthetic fertilizers of up to 62% of N and 100% of P and K compared with the CONV treatment. Although yield was similar among OA treatments, our economic budget calculations revealed that some treatments were not economically beneficial when compared to the CONV treatment (Figure 1). On average, the costs of using CFM and CCM (at either +N_{Rd} and +N_{CONV} fertilizer rate) were 33% higher (US\$440 ha^{-1}) (Table 4) than CONV. Only treatments that received CM and FM+N_{Rd} rates had lower

TABLE 3 Annual yield, total N_2O emissions and changes in soil organic C at the field experiment at Gatton Research Facility (2013–2014)

	Treatments									
	CONV	**CM+N_{conv}**	**CCM+N_{conv}**	**CM+N_{Rd}**	**CCM+N_{Rd}**	**FM+N_{conv}**	**CFM+N_{conv}**	**FM+N_{Rd}**	**CFM+N_{Rd}**	**0N**
	Horticultural field experiment									
Crop production										
Yield, t dry wt. ha^{-1}	4.4 ± 0.4a	4.2 ± 0.6a	4.4 ± 0.6a	4.1 ± 0.3a	4.5 ± 0.5a	4.5 ± 6a	5.1 ± 0.8a	4.1 ± 0.5a	4.6 ± 0.2a	2.0 ± 1.2b
N removed, kg N ha^{-1}	196.4 ± 4.1a	182.1 ± 16.3a	189.6 ± 11.4a	172.8 ± 12.6a	200.7 ± 5.4a	187.1 ± 18.5a	195.1 ± 25.8a	152.9 ± 1.3a	188.6 ± 5.6a	65 ± 33b
N_2O emissions										
Total flux, g N_2O–N ha^{-1} yr^{-1}	1,179 ± 213cde	1,523 ± 379bcd	1,127 ± 207de	1,748 ± 284bc	967 ± 309e	3,142 ± 542a	1,876 ± 683b	1,984 ± 377b	1,670 ± 309bcd	862 ± 10e
Annual N_2O emission factors, %										
Total N applied (EF)	0.10 ± 0.01ab	0.16 ± 0.09ab	0.05 ± 0.03b	0.25 ± 0.08a	0.02 ± 0.06b	0.23 ± 0.05a	0.13 ± 0.08ab	0.14 ± 0.04ab	0.11 ± 0.08 ab	–
Mineralized+N-Fer (EF_{OA})	0.10 ± 0.01bc	0.18 ± 0.1abc	0.07 ± 0.05c	0.29 ± 0.09abc	0.04 ± 0.09c	0.46 ± 0.10a	0.27 ± 0.18abc	0.40 ± 0.13ab	0.26 ± 0.18abc	–
CH_4 emissions										
Total flux, g CH_4–C ha^{-1} yr^{-1}	195.9 ± 246.5	−182.1 ± 110.3	−87.4 ± 107.2	−108.4 ± 201.5	−174.4 ± 199	−102.2 ± 183.4	−128.6 ± 147.8	−132.9 ± 72.5	−165.12 ± 72.7	–
Soil organic C										
SOC, t C ha^{-1}	25.9 ± 1.12c	27.5 ± 1.30bc	28.3 ± 1.90abc	26.5 ± 1.30bc	28.7 ± 1.90abc	30.9 ± 1.9a	28.2 ± 1.8abc	29.9 ± 2.1ab	28.8 ± 1.9abc	–
Difference in SOC, Sept. 2013–Sept. 2014, %	−4.3 ± 4.1c	−1.9 ± 4.1bc	4.1 ± 6.5abc	−2.3 ± 4.2bc	5.5 ± 6.5abc	12.22 ± 4.2a	3.9 ± 6.4abc	9.6 ± 5.9ab	5.9 ± 3.4abc	
	Composting and stockpiling experiments									
	GHG emissions									
	g CH_4–C t^{-1} fw OA		g N_2O–N t^{-1} fw OA					kg CO_2-eq t^{-1} fw OA (N_2O+CH_4)		
FM	179.0.03		102.46					49.3		
CFM	93.31		0.18					3.6		
CM	25.40		4.84					2.9		
CCM	8.55		16.07					7.1		

Note. Total CH_4, N_2O, and CO_2 from the composting and stockpiling experiment. CCM, composted chicken manure; CFM, composted feedlot manure; CM, stockpiled chicken manure; CONV, conventional N, P, and K application rate; FM, stockpiled feedlot manure; fw, fresh weight; OA, organic amendment; +N_{CONV}, conventional N fertilizer rate; +N_{Rd} reduced N fertilizer rate; SOC, soil organic carbon. Means denoted by different letters indicate significant differences between treatments ($p < .05$)

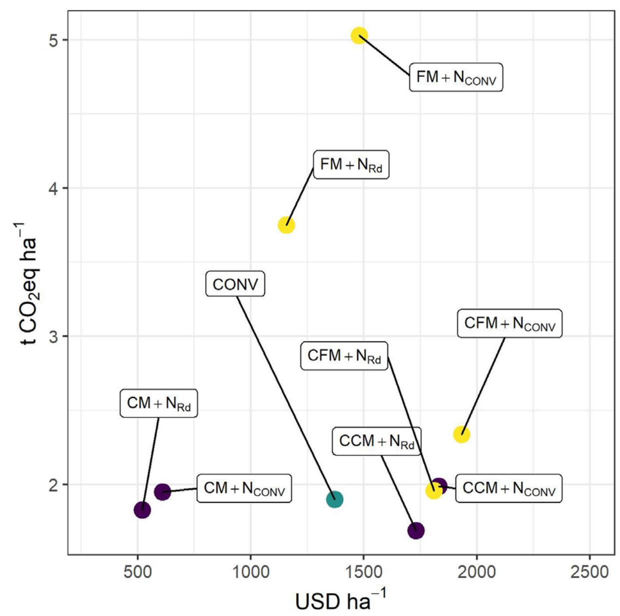

FIGURE 1 Total t $CO_2$$^-$eq ha^{-1} versus the total cost (USD ha^{-1}) of each fertilization strategy. CCM, composted chicken manure; CFM, composted feedlot manure; CM, stockpiled chicken manure; CONV, conventional N, P, and, K application rate; FM, stockpiled feedlot manure; +N_{CONV}, conventional N fertilizer rate; +N_{Rd} reduced N fertilizer rate

costs (up to 60% or ∼US$800 ha^{-1}) (Table 4) in comparison to CONV. However, the CM treatments received a reduced amount of P and K. For the CM treatments, the need for supplemental P and K fertilizer could offset the observed economic advantages in comparison to CONV.

Stockpiled manures were more economically competitive than composted manures due to the lower costs associated with material purchase. The ratio between the fertilizer replacement value (the reduced cost due to lower input of synthetic fertilizer) and the total cost of field application of composted OAs was 0.8 for both CCM+N_{Rd} and CFM+N_{Rd}, whereas those for stockpiled OAs were 7.9 and 1.3 for CM+N_{Rd} and FM+N_{Rd}, respectively. Compost purchase and transport amounted to 80% of the total cost of CCM+N_{Rd} and CFM+N_{Rd}, representing a significant economic barrier to the use of composted manure by farmers. For this study, the rates at which OAs were applied were selected focusing on replacing PAN. Given the low N availability and low N/P ratio of OAs, calculating the OA application rates focusing on replacing PAN could lead to relatively high OA application rates, resulting in potentially excessive P application and high costs when using composted OA. An alternative way to reduce the economic burden associated with the use of composted OAs could be to reduce the OA application rate with a marginal increase of supplemental N fertilizer. Also, the high application rates of AOs led to a high cost associated with the transport that was up to US$475 ha^{-1} for treatments that received FM. A possible way to further reduce the cost associated with the use of OAs could be to incentivize the cultivation of high-value crops with high plant nutrients requirement close to large manure/compost producers.

This economic assessment did not account for the additional environmental and economic benefits associated with composted OAs. The value of OAs may extend beyond nutrient replacement value and includes enhancement of agronomic and biological soil properties. These benefits are difficult to quantify economically but include improvements in chemical, physical, and biological soil quality (D'Hose et al., 2016; Diacono & Montemurro, 2010). For instance, D'Hose et al. (2016) showed that the repeated application of composted material increased disease suppressiveness against *Botrytis cinerea* on lettuce. This effect could have been economically quantified by considering the savings associated with the non- or reduced application of disease control chemicals or by considering the reduced losses, but this would have been an extremely case-specific parameter and therefore was not included in the economic calculation. For this study, the quantification of the crop nutrient supply with the OA application, however, was only considered for a relatively short time frame (1 yr). Because only about 25–35% of the organic N added to soil is released in the first year after application (De Rosa et al., 2017), it could be argued that if the long-term nutrient release is considered in the economic budget, the additional cost calculated for the composted materials as well as stockpiled would be reduced. Indeed, considering the residual effect of the first-year OA application on P and K availability (70% of P and 100% K added with OA application could be available for crops; Eghball et al. [2002]), in the second-year crop rotation it will be possible to further save up to ∼US$800 ha^{-1}. Therefore, to estimate the real value of soil OAs, nutrient replacement value should be considered over longer time frames rather than a single crop cycle application. On the other hand, the continuous application of CM would require the supplemental addition of P and K fertilizers to match the crop needs and hence increase the environmental and economic costs associated with the application of CM.

In this case study, we analyzed the economic budgets of different OA supply chains for the production of high-value horticultural crops characterized by large plant nutrient requirements. For grain cropping systems where the plant nutrient requirements and marginal net return are lower than horticultural crops, it could be argued that to obtain a positive economic budget it will be required to reduce the OA application rates in favor of synthetic fertilizers. This could be achieved by calculating the OA application rate by matching the crop P requirements rather than N because N-based OA application rates could overapply P relative to crop demand (Spiegal et al., 2020).

TABLE 4 Economic and environmental budgets of the composted and stockpiled manures supply chain and field application

	Treatments								
	CONV	CM+N_{conv}	CCM+ N_{conv}	CM+N_{Rd}	CCM+ N_{Rd}	FM+ N_{conv}	CFM+ N_{conv}	FM+ N_{Rd}	CFM+ N_{Rd}
	Economic budget, USD ha^{-1}								
Fertilizer									
N	444.18	444.18	444.18	361.07	358.21	444.18	444.18	169.07	338.15
P	403.30								
K	434.70								
Transport and spreading	41.05	27.90	27.90	26.48	26.43	27.90	27.90	23.18	26.08
Organic amendments									
Purchase		64.84	1,037.40	64.84	1,037.40	373.46	965.25	373.46	965.25
Transport and spreading		70.79	294.45	70.79	294.45	626.34	381.03	626.34	381.03
Total cost	1,323.22	607.70	1,803.93	523.17	1,716.48	1,471.88	1,818.36	1,192.06	1,710.51
Difference from CONV, %		−54.07	36.33	−60.46	29.72	11.23	37.42	−9.91	29.27
	GHG budgets, kg CO_2-eq ha^{-1}								
Fertilizer									
N	1,199.7	1,199.7	1,199.7	975.24	967.5	1199.7	1199.7	456.66	913.32
P	47.71								
K	93.05								
Transport and spreading	11	7	7	6	6	7	7	5	6
Organic amendments									
Processing (i.e., stockpiling or composting)		10.37	133.17	10.37	133.17	2,072.18	88.77	2,072.18	88.77
Transport and spreading		23.48	127.48	23.48	127.48	281.79	167.73	281.79	167.73
Field emissions	546.65	708.10	526.96	815.53	447.95	1,468.50	874.90	928.16	777.41
Total GHG, t CO_2 ha^{-1}	1.89	1.95	1.99	1.83	1.68	5.03	2.34	3.74	1.95
Difference from CONV, %		2.97	5.29	−3.17	−11.11	166.14	23.81	97.88	3.17
	Environmental credits scheme—avoided fertilizer manufacturing GHG derived from the reduction of fertilizers use								
Avoided, t CO_2-eq ha^{-1}		0.13	0.13	0.36	0.37	0.13	0.13	0.88	0.42
Net balance, t CO_2-eq ha^{-1}	1.89	1.82	1.86	1.47	1.31	4.90	2.21	2.86	1.53
Difference from CONV, %		−3.70	−1.59	−22.22	−30.69	159.26	16.93	51.32	−19.05

Note. CCM, composted chicken manure; CFM, composted feedlot manure; CM, stockpiled chicken manure; CONV, conventional N, P, and, K application rate; FM, stockpiled feedlot manure; GHG, greenhouse gas; +N_{CONV}, conventional N fertilizer rate; +N_{Rd} reduced N fertilizer rate.

3.2 | GHG budget

The GHG budget highlighted that the treatments that received FM emitted the highest CO_2-eq among all treatments. The FM+ N_{CONV} and FM+ N_{Rd} emitted 5.03 and 3.74 t CO_2-eq ha^{-1} (Table 4). On average, the total GHG emissions from the FM treatments were higher than those from CFM treatments by 90 and 115% for +N_{Rd} and +N_{CONV}, respectively. Combining CFM with reduced N fertilizer rate resulted in a similar emission level to that of CONV (1.89 t CO_2-eq ha^{-1}). Both CM and CCM in combination with the reduced fertilizer rate decreased emissions up to 11% compared with CONV, corresponding to 1.68 and 1.83 t CO_2-eq ha^{-1} for CCM+N_{Rd} and CM+N_{Rd}, respectively (Table 4; Figure 1).

The emissions generated from the transport and field application of OAs accounted for only a small proportion (1.2 and 8% for CM and FM, respectively) of the total CO_2-eq of the OA supply chain. These emissions ranged from 23.5 to 281.8 kg CO_2-eq ha^{-1} (Table 4) for treatments that received CM and FM, respectively. However, these values only account for tailpipe emissions (over the 110-km travel distance) and do not account for the possible direct emissions from OAs themselves during transportation. It can be hypothesized that transporting OAs over longer distances will increase not only the vehicular emissions but also the exposure time of OAs, thereby increasing the direct emissions from OAs. Given the lower stability of stockpiled OAs than composted OAs, it is expected that over a long haul, direct emissions from stockpiled OAs will be higher than composted OAs.

Manure processing (i.e., stockpiling and composting) was responsible for 55.2% of the total direct emissions from FM+N_{Rd} and only 4.5% for CFM+N_{Rd}, whereas it accounted for 7.9 and 0.6% of the total emissions for CCM+N_{Rd} and CM+N_{Rd}, respectively. The lower field emissions of treatments that received CCM in comparison to CM at the same rate of N fertilizers compensated the higher processing emissions of CCM (7.1 kg CO_2-eq t^{-1} fw OA) than CM (2.9 kg CO_2-eq t^{-1} fw OA) (Table 3). However, although the composting process lowered N_2O and CH_4 emissions (Table 3) due to the increased aeration as a consequence of turning operations, the composting process could potentially increase other N losses, such as via ammonia volatilization (Amon et al., 2001), reducing the environmental benefit observed from the field application.

In the field experiment, the application of composted manure in combination with reduced fertilizer rate did not increase N_2O emissions (CCM+N_{Rd} 967 ± 309 g N_2O–N ha^{-1} yr^{-1} and CFM+ N_{Rd} 1,670 ± 309 g N_2O–N ha^{-1} yr^{-1}) in comparison to CONV (1,179 ± 213 g N_2O–N ha^{-1} yr^{-1}) (Table 3), whereas stockpiled feedlot manure with a standard fertilizer rate (FM+N_{CONV}) resulted in the highest N_2O emissions (3,142 ± 542 g N_2O–N ha^{-1} yr^{-1}) (Table 3). Reducing N fertilizer rate in the FM treatment (FM+N_{Rd}) lowered N_2O emissions by 37% (1,984 ± 377 g N_2O–N ha^{-1} yr^{-1}) as compared to FM+N_{CONV}. The lowest N_2O emissions among the fertilized treatments were recorded in the CCM+N_{Rd} (967 ± 309 g N_2O–N ha^{-1} yr^{-1}) and were not significantly different from the emissions measured from the unfertilized treatment (0N, 862 ± 10 g N_2O–N ha^{-1} yr^{-1}) (Table 3). Generally, the application of composted OAs in combination with reduced fertilizer rate lowered soil N_2O emissions in comparison to stockpiled OAs under the same fertilizer strategy. This N_2O emission reduction can be attributed to N and C limitation for soil microorganisms. Composted OAs, when compared to raw OAs, generally contain less easily degradable organic matter and a higher percentage of recalcitrant material (high stability) that favors N immobilization due to the lower C/N ratio (Bernai et al., 1998). Easily degradable organic matter also serves as an O_2 sink as well as a C source for heterotrophic denitrification.

The calculated EFs following the IPCC methodology that took into account the yearly total N applied with OAs plus N-fertilizer ranged from 0.02% for CCM+N_{Rd} to 0.25% for CM+N_{Rd} (Table 3) and were lower than the EF proposed by the current IPCC methodology, which considers 1% for total N applied lost as N_2O. Furthermore, considering only the estimated PAN released from OAs plus the total N-fertilizer applied, the EF_{OA} values were still lower than 1% and ranged from 0.04% for CCM+N_{Rd} to 0.46% for FM+N_{CONV} (Table 3). However, other studies using OAs in combination with synthetic fertilizer report EFs substantially higher (1.7–2.9%) than the IPCC default of 1% (Charles et al., 2017; Liyanage et al., 2020). These results highlight the uncertainty associated with the use of the standard EF when estimating N_2O losses following the application of OAs.

The field-measured CH_4 fluxes ranged from −195.99 ± 246.55 g CH_4–C ha^{-1} yr^{-1} for CONV to −87.42 ± 107.2 g CH_4–C ha^{-1} yr^{-1} for CCM+N_{conv} and the application of OAs did not increase annual soil CH_4 (Table 4). The calculation of the cumulative fluxes highlighted a net uptake of CH_4 among all treatments (Table 3) most likely driven by the nonanoxic conditions of the soil at the experimental site because aerated soils are generally a net sink for CH_4 (van Delden et al., 2018).

Another positive effect observed with the application of OAs is the increase of SOC content after only a single annual application, though the changes in SOC were significantly higher than CONV only for treatments that received FM (Table 3). The highest SOC of 30.9 ± 1.9 t C ha^{-1} (0–0.3 m) was observed in FM+N_{CONV}, followed by treatments that received composted OAs (CFM and CCM) (Table 3). The lowest levels of SOC content were observed in CM+N_{Rd} and CONV, with 26.5 ± 1.30 and 25.9 ± 1.12 t C ha^{-1} (Table 3). With the annual application of OAs, the FM treatments received a total of 7 t C ha^{-1}, whereas for CFM and CCM an average of 2.9 t C ha^{-1} was applied (Table 1). Because the net difference in soil C content at the end of the annual crop rotation between CONV and FM treatments was only from 4 to 5 t C ha^{-1} and for CCM and CFM the average differences were 2.8 and 2.6 t C ha^{-1}, respectively, it can be argued that the majority of C applied with the composted material was retained in the soil. This can be attributed to the higher stability of the composted products in comparison to raw OAs. Therefore, the field application of composted OAs might increase SOC stocks while reducing reactive N pollution, but the latter is only achievable if the plant nutrients released from OAs are accounted for in the crop-rotation fertilization strategy.

4 | CONCLUSIONS

In this case study, we analyzed the environmental and economic budgets of different OA supply chains from production, transportation, to land application. The OAs were used as a partial substitution for synthetic fertilizers. Our analysis demonstrated that the application of composted OAs in combination with a reduced N fertilizer rate (N_{Rd}) always resulted in lower GHG emissions compared with stockpiled manures (Figure 1). However, the economic burden associated with the purchase and transport of composts might present a barrier to the use of composted OAs by farmers. Composted OAs were on average three times more expensive than those of stockpiled manures, but if long-term nutrient release from OAs is taken into account, especially K and P considering their relatively low mobility in the soil, additional savings are possible. If only considering the nutrient replacement value of OAs, farmers will only purchase OAs in substitution of synthetic fertilizer if the price of OAs is lower or equal to the equivalent nutrient value of synthetic fertilizer or if the environmental benefits provided with the OA application exceed the extra cost associated with the use of OAs (Leip et al., 2019). Because income from soil carbon sequestration from OAs alone is unlikely to bridge this financial gap, particularly in the short-term, this study proposes that future policy should develop methodologies to include avoided GHG emissions from OA application. Our case study showed that the avoided emissions due to synthetic fertilizer reduction (calculated as the difference of total GHG generated from N, P, and K fertilizer manufacturing between CONV and OA treatments) were 0.37 and 0.42 t CO_2-eq ha^{-1} for CCM+N_{Rd} and CFM+N_{Rd}, respectively (Table 4). Considering these avoided emissions in the GHG budgeting indicated that our N_{Rd} treatments resulted in a 30.4% reduction in GHG emissions at a similar crop yield level when compared to the control treatment (CONV). Considering an average price for a Carbon Credit Unit of US$11.2 t^{-1} CO_2-e (Commonwealth of Australia, 2021), the additional economic return for avoided emissions for CCM+N_{Rd} and CFM+N_{Rd} would be US$4.07 ha^{-1} and US$4.62 ha^{-1}, respectively.

Our case study demonstrated that the N_2O EFs of synthetic N fertilizer and OA supplementation could be well below 1%, which is the default EF by the IPCC (Kroeze et al., 1997). The EFs of OA and synthetic N fertilizers were 0.23 and 0.14, averaged across all treatments, respectively (Table 3). This high discrepancy observed between default EFs and actual measured field and manure processing emissions highlights the importance of using actual measured GHG emissions to accurately estimate the environmental impact of the manure supply chain. Therefore, to incentivize the use of OAs as an environmentally and economically sustainable substitute for synthetic fertilizers, the reduction in GHG emissions associated with the use of OAs should be taken into account into actual C sequestration programs with a refined N_2O emission factor used for GHG emission accounting.

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AUTHOR CONTRIBUTIONS

Daniele De Rosa: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Johannes Biala: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Writing-original draft; Writing-review & editing. Trung H. Nguyen: Data curation; Investigation; Methodology; Software; Writing-original draft; Writing-review & editing. Elaine Mitchell: Conceptualization; Investigation; Methodology; Writing-review & editing. Johannes Friedl: Conceptualization; Investigation; Methodology; Writing-review & editing. Clemens Scheer: Data curation; Funding acquisition; Investigation; Methodology; Project administration; Writing-review & editing. Peter R. Grace: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Validation; Writing-review & editing. David W. Rowlings: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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