Reducing ammonia losses during composting of chicken manure without altering economic outcomes

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by J. Biala

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Researcher/Author Contact Details

Name:	Mr Johannes Biala
Address:	Centre for Recycling of Organic Waste and Nutrients University of Queensland, Gatton QLD 4343
Phone:	0409 062 613
Email:	biala@optusnet.com.au

In submitting this report, the researcher has agreed to Australian Eggs Limited publishing this material in its edited form.

Australian Eggs Limited Contact Details:

Australian Eggs Limited
A.B.N: 66 102 859 585
Suite 6.02, Level 6, 132 Arthur St
North Sydney NSW 2060

Phone:	02 9409 6999
Fax:	02 9954 3133
Email:	research@australianeggs.org
Website:	www.australianeggs.org.au

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Foreword

This project was conducted to investigate whether blending layer manure with increasing quantities of sawdust would be able to reduce ammonia losses and greenhouse gas emissions during the composting process, and how implementation of this emission reduction measure would affect economic performance indicators of the composting operation.

This project was funded from industry revenue which is matched by funds provided by the Australian Government.

This report is an addition to Australian Eggs Limited's range of peer reviewed research publications and an output of our R&D program, which aims to support improved efficiency, sustainability, product quality, education and technology transfer in the Australian egg industry.

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Table of Contents

Foreword ... ii
Acknowledgments ... iii
Table of Contents ... iv
List of Tables ... v
List of Figures ... vi
Abbreviations ... vii
Executive Summary ... viii
Overall Conclusions ... x
1 Introduction ... 1
2 Materials and methods ... 3
2.1 Overview ... 3
2.2 Trial site ... 3
2.3 Assessed manure management options ... 4
2.4 Trial design ... 4
2.5 Composting ... 7
2.6 Timeline ... 8
2.7 Monitoring ... 8
2.8 Gas sampling and analysis ... 8
2.8.1 Manual ammonia gas sampling ... 8
2.8.2 Automated GHG sampling and analysis ... 11
2.9 Calculating gas fluxes ... 12
2.9.1 Ammonia ... 12
2.9.2 Greenhouse gases and carbon dioxide ... 13
2.10 Gas fluxes per pile/windrow ... 14
3 Results ... 15
3.1 Temperature profiles ... 15
3.2 Material characteristics ... 17
3.3 Greenhouse gas emissions ... 20
3.3.1 Methane ... 20
3.3.2 Nitrous oxide ... 22
3.3.3 Ammonia ... 24
3.3.4 Emissions per tonne manure/feedstock ... 26
3.4 Mass and nutrient balance for composting ... 28
3.4.1 Mass balance ... 28
3.4.2 Nutrient and carbon balance ... 31
3.5 Economic assessment ... 31
4 Discussion ... 33
4.1 Trial results ... 33
4.2 Determination of emission factors ... 37
5 References ... 39
6 Appendix ... 42

List of Tables

Table 1 Mixing ratios of layer chicken manure and sawdust 4
Table 2 Types and quantities (L) of liquids added to different windrows during composting 7
Table 3 Solids and nutrient concentrations (mg/L) in liquids added to windrows 7
Table 4 Values for nitrogen, carbon and C:N ratio determined in raw and composted layer chicken manure with the Dumas method at the beginning and end of the trial period .. 17
Table 5 Changes in key chemical characteristics during stockpiling and composting of layer chicken manure 18
Table 6 Combined gas emissions per tonne wet/dry manure and per tonne wet/dry feedstock 27
Table 7 Assumed fresh matter compost yield if moisture content was 35% for all products 29
Table 8 Fresh matter (FM) and dry matter (DM) mass balance (t) for composting of layer chicken manure with addition of varying quantities of sawdust 30
Table 9 Nutrient and carbon balance (kg) for composting of layer chicken manure with addition of varying quantities of sawdust 30
Table 10 Economic implications of composting chicken manure with different quantities of sawdust 32
Table 11 Annual nutrient load and value in compost generated from layer chicken manure and different quantities of sawdust 32
Table 12 Greenhouse gas emissions from stockpiling and composting of animal manures 34
Table 13 Key characteristics of blended feedstock for composting Windrows A-C 35
Table 14 Default emission factors for 'waste composting' 38

List of Figures

Figure 1 Rainfall and minimum/maximum temperatures recorded at Pittsworth (rainfall) and Toowoomba (temperature) during the trial period 4

Figure 2 Blending chicken manure and sawdust (Windrow C) 5

Figure 3 Schematic outline of the windrows and Stockpile, including manual ammonia sampling units and automatic flux chambers 6

Figure 4 Adding liquid to windrow prior to turning 8

Figure 5 Schematic set-up for ammonia gas sampling 9

Figure 6 Flow-through flux chamber for manual ammonia sampling 10

Figure 7 Arrangement for ammonia gas sampling in the field 10

Figure 8 Automated (left) and manual (right) gas sampling chambers 12

Figure 9 Daily average temperatures measured inside the Stockpile and windrows during the four-month trial period 16

Figure 10 Changes in total nitrogen (TKN), total phosphorous (TKP), organic carbon (Org C) and the C:N ratio (C:N) during windrow composting (WR A, WR B, WR C) and stockpiling (Raw) of layer chicken manure 19

Figure 11 Dried surface of stockpiled chicken manure ..... **Error! Bookmark not defined.**

Figure 12 Daily methane emission rates per square metre (top) and for each pile or row (bottom) from stockpiled and composted layer chicken manure 21

Figure 13 Cumulated methane emissions from stockpiled and composted layer chicken manure 22

Figure 14 Daily nitrous oxide emission rates per square metre (top) and for each pile or row (bottom) from stockpiled and composted layer chicken manure 23

Figure 15 Cumulated nitrous oxide emissions from stockpiled and composted layer chicken manure 24

Figure 16 Daily ammonia emission rates per square metre (top) and for each pile or row (bottom) from stockpiled and composted layer chicken manure 25

Figure 17 Cumulated ammonia emissions from stockpiled and composted layer chicken manure 26

Figure 18 Changes in moisture and volatile solids levels during composting (WR A, WR B, WR C) and stockpiling (Raw) of chicken manure 36

Abbreviations

C:N ratio	Carbon to nitrogen ratio
CO_2-e	Carbon dioxide equivalent
DAE	Days after establishment
DM	Dry matter
FM	Fresh matter
g	Gram
GHG	Greenhouse gas emissions
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
L	Litre
m	Metre
mg	Milligram
min	Minute
QUT	Queensland University of Technology
t	Tonne
tpa	Tonnes per annum
v/v (%)	volume/volume (per cent)
w/w (%)	weight/weight (per cent)

Executive Summary

Greenhouse gas (methane and nitrous oxide) and ammonia emissions were monitored during the stockpiling and composting of layer chicken manure at a commercial composting operation that processes about 30,000 tonnes per annum of layer chicken manure. Manure was co-composted with varying quantities of sawdust, achieving initial carbon to nitrogen (C:N) ratios of approximately 7:1, 14:1 and 21:1 for the composting feedstock. Methane and nitrous oxide emissions were automatically monitored and analysed *in situ*, while ammonia emissions were monitored by means of regular manual sampling in acid traps during the 128-day monitoring period.

Project activities included not only measuring gaseous emissions and determining emission factors, but also determining mass, nitrogen and carbon balances for each compost feedstock and, most importantly, assessing the economic impact of composting chicken manure with various sawdust amendments.

The obtained results allowed us to draw the following conclusions:

1. Methane emissions were relatively low from stockpiled manure and very low when manure was composted with a little sawdust. Emissions increased as the proportion of sawdust increased.
2. Methane emissions started about 14 days after establishment (DAE) of the Stockpile and windrows, and peaked between 30 and 75 DAE, with daily emission rates being highest for the manure amended windrow with the highest proportion of sawdust.
3. Cumulated methane emissions (per m^2) were highest for the windrow with the highest sawdust addition, followed by the Stockpile.
4. High daily nitrous oxide fluxes were observed in the windrow with low sawdust, with emissions increasing towards the end of the monitoring period.
5. Cumulated nitrous oxide emissions (per m^2) were highest for the windrow with low sawdust, with similar values for windrows with intermediary and high sawdust. Cumulated emissions from the Stockpile were very low.
6. Ammonia emissions did not show a clear pattern, other than that fluxes from the Stockpile were often lowest.
7. Cumulated ammonia emissions (per m^2) were highest for the windrow with intermediary sawdust, with similar values for windrows with low and high sawdust. Cumulated emissions from the Stockpile were lowest.
8. Combined methane and nitrous oxide emissions expressed per tonne wet feedstock were similar to those recorded previously.
9. Total greenhouse gas (GHG) emissions, including values for ammonia emissions, and expressed as CO_2-e per tonne wet feedstock, were comparatively low, amounting to 7.19 kg for the Stockpile, and 11.5 kg, 14.0 kg and 24.8 kg for windrows with low, intermediary and high proportion of sawdust.
10. Composting of layer chicken manure with an increasing proportion of sawdust did not result in reduced GHG emissions neither per tonne wet feedstock nor per tonne wet or dry manure.
11. Emissions from all assessed manure management options were well below the Australian default emission factors for 'waste composting'.

12. The mass and nutrient balance showed dry matter losses during composting of 14% to 19%, while 33% to 45% of organic carbon was lost.
13. Nitrogen losses amounted to over 55% for manure that was composted with low and intermediary levels of sawdust, and 37% when sawdust addition was high.
14. The monetary value of current nitrogen losses at the Organic Nutrient operation amounts to about $730,000 per annum.
15. Blending manure with more sawdust increases input and operational costs, hence requires adjustments in selecting bulking materials, determining prices and pricing structures, and finding target markets in order to make nitrogen loss reductions economically viable for composting operations.
16. To make nitrogen conservation measures viable in the context of manure management it is necessary for farmers to fully appreciate the nutrient value and other beneficial effects associated with using organic soil amendments.

Overall Conclusions

Nitrogen retention is key to high value hen manure compost.

Composting of poultry manure provides various advantages including pathogen and odour reduction and ease of handling, storage and spreading. Importantly, there is growing demand for nitrogen-rich compost from high value horticultural markets due to significantly lower risks than using raw manure, which presents an opportunity for additional income for layer operations. Yet, composting of poultry manure can result in high nitrogen losses through emission of ammonia gas of up to 50% or more. Nitrogen losses are increased when there is a low carbon to nitrogen (C:N) ratio of the composted material. Adequate composting of poultry manure requires blending with additional carbon-rich materials, such as sawdust or wood, chips which adds compost production costs. This project sought to clarify what level of sawdust could be incorporated to maximise nitrogen retention for hen manure composting without impacting on the economic performance of the operation.

The key findings of the project include:

Status quo

- Blending of layer hen manure with 20% sawdust (volume based) provides composting raw material with a C:N ratio of 7:1. High ammonia levels suppress microbial activity which slows composting with temperatures still around 70°C after four months of composting.
- Nitrogen losses amount to over 55%, representing an economic loss of approximately $25 per tonne fresh manure or around $250,000 per annum for a facility that composts 10,0000 tpa of layer hen manure.

Nitrogen retention

- Nitrogen emissions (i.e. ammonia) were observed throughout the four months monitoring period in no particular pattern and not only during the initial composting phase. Surprisingly, ammonia losses from the stockpile (without sawdust) were often lowest.
- No reduction of nitrogen losses was observed when manure was blended with sawdust to a C:N ratio of 14:1, yet, nitrogen losses were reduced to 37% when more sawdust was added to reach a C:N ratio of 21:1.

Economic outcomes

- Increased input and operational costs associated with adding more sawdust could not be offset by increased compost volumes being sold at current prices and pricing structures.
- To render the reduction of nitrogen losses economically viable, it is necessary to obtain cheaper bulking materials, increase sales prices, change pricing structures or find high value markets for the compost other than horticulture (such as growing or potting media).

Implications

- Composting hen manure can result in significant nitrogen losses which represent substantial economic losses. Reduction of nitrogen losses will ultimately be economically viable if compost users recognise and account for the full nutrient value of composted hen manure and all other benefits associated with its use.

1 Introduction

Research carried out within the National Agricultural Manure Management Program showed that methane and nitrous oxide emissions from stockpiled and composted layer chicken manure were low compared to emissions measured during stockpiling and composting of dairy, feedlot and pig manure (Rowlings & Biala 2016). It was assumed that high ammonia concentrations in the stockpiled and also composted chicken manure inhibited many microbial processes, including the formation of methane and nitrous oxide. While recorded methane and nitrous oxide emissions were low, there were indications that nitrogen losses through ammonia volatilisation were high, although nitrogen losses other than through nitrous oxide emissions were not quantified at the time. Many examples in the literature document high ammonia losses during composting of animal manures (e.g. Kithome et al. 1999; Peigné & Girardin 2004; Jiang et al. 2011), with losses reaching 30% to 70% of nitrogen contained in the manure. It is well known that low carbon to nitrogen (C:N) ratios of the compost mix, combined with high pH and high temperatures, can result in significant ammonia losses (Pardo et al. 2015). Washington State University (2016) showed, for example, that increasing C:N ratios in manure composting from 20:1 to 35:1 corresponded with a reduction in nitrogen losses from 39% to 0%.

It is very difficult if not impossible to compost layer chicken manure on its own due to its physical and chemical properties. To facilitate the composting process, the manure needs to be blended with dry, carbonaceous bulking material such as sawdust, wood chips, rice hulls, or shredded vegetation residues. However, many on-farm composting operations minimise use of these bulking materials as they have to be purchased and brought to the farm, increasing operating and compost production costs. Use of off-farm resources for co-composting usually requires the operation to obtain planning and regulatory permits. The composting facility, where the trials were conducted, holds an environmental licence allowing it to co-compost off-farm residues. Yet, the chicken manure is amended with only 20% (v/v) of sawdust, resulting in compost feedstock with characteristics (C:N ratio = 7, pH = 8) that make significant ammonia losses during composting highly likely.

Over time, a range of management techniques and feedstock amendments were assessed regarding their capacity to reduce ammonia losses during the composing of layer manure. Such research assessed a broad range of diverse additives (Koenig et al. 2005), or evaluated specific products such as zeolite (Kithome et al. 1999) and flue gas desulphurisation gypsum (Tubail et al. 2008; Guo et al. 2016). Yet, it seems that companies that compost animal manures and other feedstock with low C:N ratio are unwilling to use additives as a means of reducing nitrogen losses via ammonia volatilisation. The reason for this might be (i) that reductions in nitrogen losses through additives are not necessarily high enough (Guo et al. 2016) to make a difference to the economic value of the generated compost, and (ii) that the costs of additives and the rate at which they have to be used make such activities economically unviable (Kithome 1998).

Consequently, a large-scale trial was established at a layer chicken manure composting operation to investigate if blending the layer manure with increasing quantities of sawdust would be able to markedly reduce ammonia losses and greenhouse gas emissions during the composting process, and how implementation of this simple emission reduction measure would affect economic performance indicators of the composting operation.

The trial aimed to generate the following scientific, technical and economic information:

1. Ammonia losses from composted layer chicken manure that was amended with varying amounts of sawdust.
2. Greenhouse gas (CH4, N_2O, CO_2) emissions from composted layer chicken manure that was amended with varying amounts of sawdust.
3. Nutrient (N, P, K) and carbon content, and their monetary value in the generated finished compost products.
4. A mass, nitrogen and carbon balance for each of the three compost mixes.
5. Assessment of the economic viability of adding increased quantities of sawdust for the composting of layer chicken manure, and assurance that improved production processes will not alter economic outcomes.

2 Materials and methods

2.1 Overview

Carrying out the field trial involved the following key activities:

1. Layer chicken manure with varying sawdust amendments representing standard (C:N ratio = 7) and improved management practices (C:N ratio = 14 and 21) were composted for a period of 18 weeks. As a comparison, unamended manure was stockpiled for the same period of time.
2. Direct (methane [CH_4] and nitrous oxide [N_2O]) and indirect (ammonia [NH_3]) greenhouse gas emissions from stockpiled and composted layer chicken manure were determined. Emissions of greenhouse gases and carbon dioxide [CO_2] were monitored automatically with an *in situ* sampler and gas chromatograph located at the composting site. Ammonia emissions were monitored regularly by means of manual sampling acid traps and subsequent laboratory analysis.
3. Composting process indicators were monitored continuously (temperature) or at time of turning (bulk density, moisture content).
4. Compost and manure samples were taken at the beginning and end of the composting process, and also every time the windrows were turned. Samples were analysed for moisture, pH, mineral and total nitrogen, and also for organic carbon content. Each of the three screened compost products was characterised comprehensively.
5. A mass, nitrogen and carbon balance, accounting for input, gaseous losses and output, was established for each of the three compost mixes.
6. The economic impact of composting chicken manure with various sawdust amendments was assessed.

2.2 Trial site

Emission measurements from stockpiled and composted chicken manure were taken at the Organic Nutrients composting site, located at Homestead Road, Felton, Queensland (151.41E/27.49S), about 50 km south-west of Toowoomba. Approximately 30,000 tonnes of layer chicken manure and 4,000 tonnes of sawdust were processed at the site during 2014/15.

The trial period, which spanned the period from 18 May to 25 October 2017, was dominated by relatively mild and dry winter conditions with minimum temperatures often dropping below 10°C and maximum temperatures mainly oscillating around 20°C, except towards the end of the trial when maximum temperatures exceeded 30°C. Total rainfall during the four-month gas emission monitoring period to 22 September amounted to 57 mm, with another 148 mm falling until 25 October, when the compost was screened and sampled for the last time. Rainfall distribution and daily minimum/maximum temperatures recorded at nearby weather stations are shown in Figure 1.

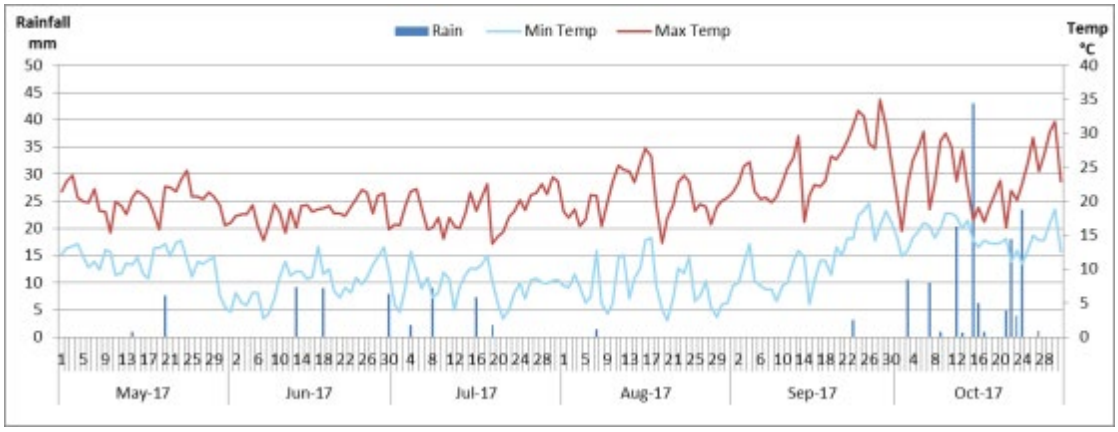


Figure 1 **Rainfall and minimum/maximum temperatures recorded at Pittsworth (rainfall) and Toowoomba (temperature) during the trial period**

2.3 Assessed manure management options

Emissions were assessed from stockpiled layer chicken manure and also from composted manure that was blended with various quantities of sawdust to achieve C:N ratios of approximately 7:1, 14:1 and 21:1 for the composting mix. Hence, the following manure management options were assessed:

1. Stockpiling (manure only);
2. Composting in windrows
   Windrow A – C:N ratio: 7:1
   Windrow B – C:N ratio: 14:1
   Windrow C – C:N ratio: 21:1.

2.4 Trial design

The Stockpile and windrows were established on 18 May by blending chicken manure and sawdust at the ratios shown in Table 1.

Table 1 **Mixing ratios of layer chicken manure and sawdust**

Treatment	Chicken Manure		Sawdust		Compost Mix
	Weight (t)	Volume (m^3)	Weight (t)	Volume (m^3)	Weight (t)
Stockpile	25.71	30.8	0	0	-
Windrow A	87.84	103.5	6.86	20.7	94.70
Windrow B	46.21	54.1	22.00	67.0	68.21
Windrow C	30.06	37.5	28.28	86.0	58.34

Three separate windrows were established using a front end loader with scales to place a predetermined quantity of chicken manure in a row and then to cover it with a predetermined quantity of sawdust. Subsequently the windrows were turned four times to blend the manure and sawdust (Figure 2). Each windrow measured between about 25 m and 35 m in length throughout the trial. An amount of 25.7 t of unamended layer chicken manure was tipped from trucks straight into a stockpile. Once the Stockpile was established, nothing else was done until the trial had been completed, i.e. the stockpiled manure was neither turned nor watered.

Figure 2 shows the windrow turner blending manure and sawdust. The non-uniform distribution of the sawdust along the windrow and the light sawdust sitting on top of the heavier manure is likely to have resulted in non-uniform material characteristics until the row has been turned and mixed several more times.

The large-scale Stockpile and windrows were not replicated, but multiple manual ammonia sampling units and automatic flux chambers on the stockpiled and composted materials allowed spatial variations in material characteristics and emissions to be captured. Three manual ammonia sampling units and three automatic flux chambers were placed on the Stockpile and each of the windrows (see Figure 3).



Figure 2 Blending chicken manure and sawdust (Windrow C)

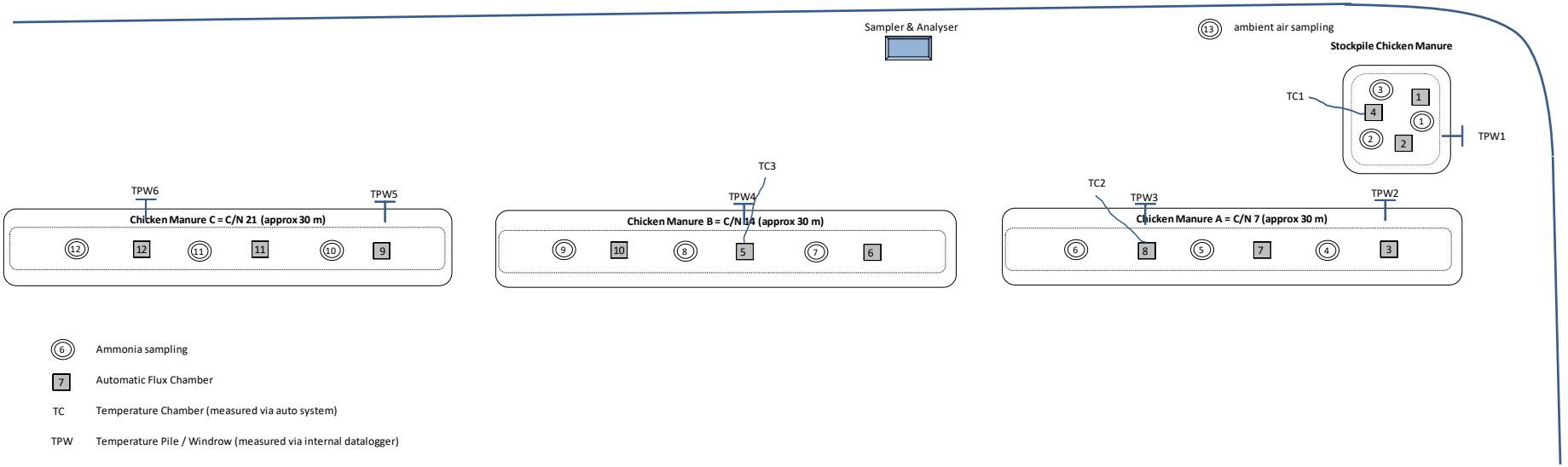


Figure 3 Schematic outline of the windrows and Stockpile, including manual ammonia sampling units and automatic flux chambers

2.5 Composting

After establishment, the windrows were turned with a dedicated turner eleven times, namely on 26 May, 5 June, 12 June, 22 June, 3 July, 18 July, 1 August, 21 August, 22 August, 31 August and 15 September. If necessary, piggery effluent from a neighbouring farm or water from the dam capturing run-off from the composting site was used to add liquid to the windrows via overhead spray prior to turning (Figure 4). As water was added on a needs basis, windrows with lower manure to sawdust ratio (Windrow B and C) received more liquid than Windrow A, which had the highest manure to sawdust ratio (5:1. v/v). Table 2 shows types and quantities of liquids added to windrows and Table 3 shows their respective nutrient content.

Table 2 Types and quantities (L) of liquids added to different windrows during composting

Date	Type	Windrow A	Windrow B	Windrow C
5 June	Piggery effluent	0	2,500	5,000
12 June	Piggery slurry	0	2,250	3,375
22 June	Dam water*	0	2,200	5,300
3 July	Piggery effluent	0	3,750	3,750
21 August	Piggery effluent	6,500	6,500	6,500
22 August	Piggery effluent	2,500	2,500	2,500

* Water from dam capturing run-off from composting site.

Table 3 Solids and nutrient concentrations (mg/L) in liquids added to windrows

	Piggery slurry	Dam water	Piggery effluent	Piggery effluent
Date	12 June	22 June	3 July	21 August
Total solids (TSS)	15,000	396	602	516
Ammonium (NH_4-N)	1,260	39.0	62.3	45.8
Nitrate + Nitrite (NO_x-N)	< 0.10	< 0.20	< 0.20	< 0.20
Total N	2,750	239	327	324
Reactive P	79.8	9.22	8.11	7.68
Total P	879	55.6	83.1	81.7
Total K	1,600	833	1,460	1,580



Figure 4 Adding liquid to windrow prior to turning

2.6 Timeline

The trial was established on 18/19 May 2017 and the last gas emission samples were taken on 22 September. Hence, stockpiling and composting of chicken manure was monitored for 126 days (18 weeks). Product samples were taken every time the windrows were turned, for the last time on 15 September. However, screened compost, ready for sale, was also sampled, but due to adverse weather conditions and malfunctioning equipment, this occurred only on 25 October. Stockpiled manure was sampled on 3 November.

2.7 Monitoring

Status and progress of the composting process was monitored by:

- measuring temperatures at hourly intervals inside the Stockpile and windrows with two temperature data loggers (TPW, 1.5 m probe) each recording temperatures at approximately 1 m below the surface;
- the handheld oxygen probe (AM 39-K) could not be used as it malfunctioned due to high ammonia and possibly sulphur concentrations inside the composted material.

The chemical analysis was carried out by a commercial laboratory according to methodologies described in the Australian Laboratory Handbook of Soil and Water Chemical Methods (1992).

2.8 Gas sampling and analysis

2.8.1 Manual ammonia gas sampling

Based on literature information (e.g. Ndegwa et al. 2009) and preliminary trial results involving the use of differently shaped gas sampling chambers, variation of air flow rates and duration (= sampling time) and use of sulfuric acid at various strength (molarity), the following sampling methodology was found to be appropriate for expected ammonia fluxes.

Figure 5 shows the set-up that was used for capturing ammonia emitted from stockpiled and composted chicken manure. A vacuum pump (Welch, WOB-L Pump 2511) was used to generate air flow of five litres per minute, which was delivered via plastic tubing to the air inlet of the gas sampling chamber. The air inlet was located just above the surface of the manure/compost, while the air outlet was located on the opposite side of the chamber, just below the lid of the chamber, approximately 0.13 m higher than the inlet (Figure 6). A teflon coated plastic tube connected the air outlet to a flask containing 400 ml of 0.5 molar sulfuric acid, which trapped ammonia contained in the air according to the chemical reaction:

$H_2SO_4 + 2NH_3 \Rightarrow (NH_4)_2SO_4$ (Eq. 1)

A fish tank air disperser was used to ensure that air bubbles were small, allowing as much ammonia to be captured in the sulfuric acid as possible. Subsequently, the air was directed through de-ionised water (via the air dispenser) before returning to the pump to prevent any acid from reaching and damaging the vacuum pump. Figure 7 shows the sampling equipment as it was used in the field.

After connecting a new flask with sulfuric acid, gas sampling was initiated by simultaneously switching on the pump and placing the lid on top of the flux chamber. Sampling was stopped after 20 minutes by turning off the pump. The mobile sampling equipment was moved from one flux chamber to the next until samples from all 13 chambers were taken. Sampling specifications were as follows:

Emission surface area: 0.0434 m^2

Air flow rate: 5 L/min

Sampling time: 20 min

Strength of sulfuric acid: 0.5 molar

Volume 0.5 mol sulfuric acid: 400 ml

Three round flow-through flux chambers (diameter = 0.235 m) each were placed on the Stockpile and each of the windrows. In addition, one flux chamber was placed on bare soil adjacent to the trial site to determine ambient ammonia fluxes. Gas sampling occurred twice per week for the first five weeks of the trial, and then at weekly intervals until the last sampling event on 20 September. Emissions from composted and stockpiled manure were measured for 18 weeks, totalling 20 sampling events. Flux chambers were removed from windrows prior to turning, and returned afterwards. Samples were taken no less than three days after turning, except when potential variations in ammonia fluxes were assessed directly after windrow turning. Flux chambers on top of the stockpiled manure were never moved during the trial period.

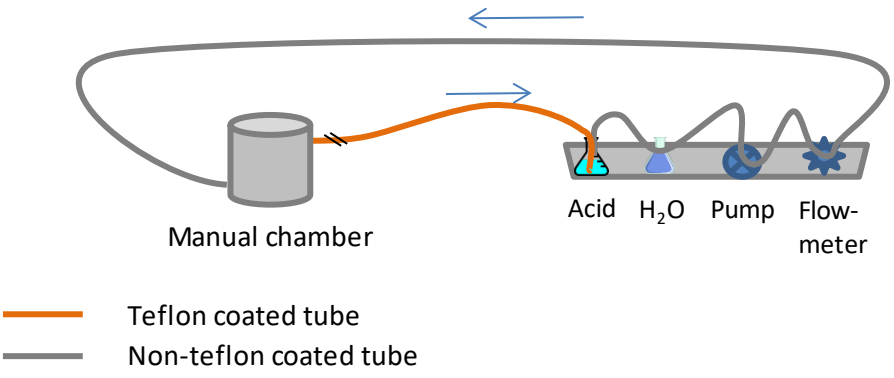


Figure 5 Schematic set-up for ammonia gas sampling

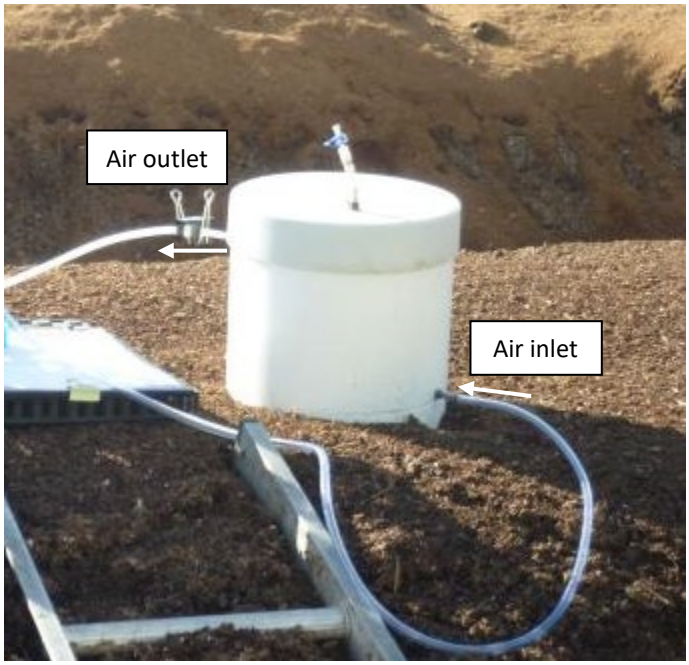


Figure 6 **Flow-through flux chamber for manual ammonia sampling**

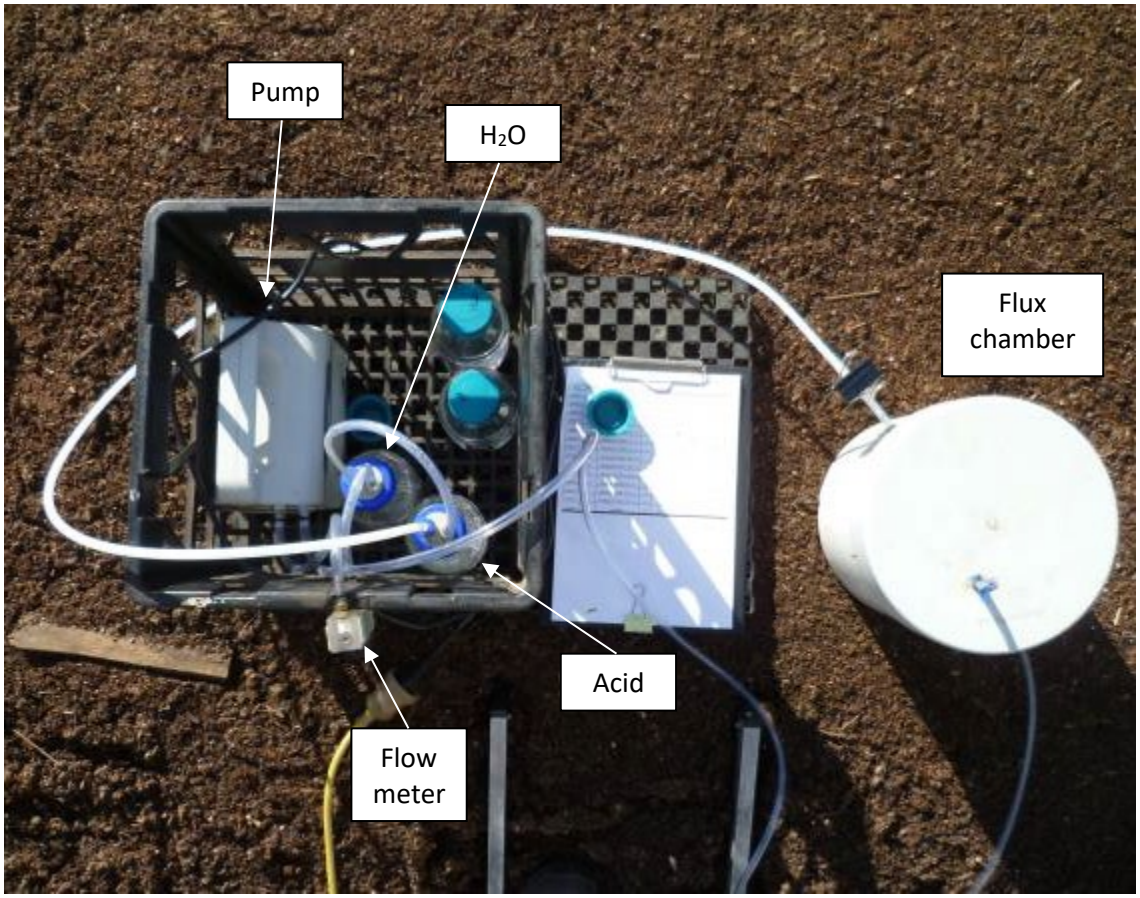


Figure 7 **Arrangement for ammonia gas sampling in the field**

Samples, contained in acid flasks, were taken to the QUT laboratory where sub-samples (100 ml) were prepared and refrigerated until ammonium nitrogen content was determined colourimetrically in 2 ml sub-samples with a Gallery™ Automated Photometric Analyzer (ThermoFisher Scientific).

2.8.2 Automated GHG sampling and analysis

Automated gas sampling and analysing techniques were employed to determine fluxes of GHGs nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) from stockpiled and composted chicken manure. Twelve rectangular automated sampling chambers were used, three of which were placed on the stockpiled manure and three on each of the three windrows (Figure 3).

The automated system consisted of pneumatically operated static chambers (Figure 8), linked to an automated sampling system, an *in situ* gas chromatograph and an infrared gas analyser. The clear acrylic glass chambers covered a surface area of 0.25 m^2 (0.5 m x 0.5 m), had a height of 0.15 m, a volume of 0.0375 m^3, and were secured to a stainless steel base that allowed penetration of the manure/compost to a depth of 0.1 m.

Nitrous oxide (N_2O) and methane (CH_4) concentrations were determined using a gas chromatograph (SRI GC8610, Torrance, CA, USA) equipped with ^{63}N Electron Capture Detector (ECD) for N_2O and a Flame Ionisation Detector (FID) for CH_4. Carbon dioxide (CO_2) was measured continuously with a non-dispersive infrared CO_2 analyser (LI-820; LI-COR, Lincoln Nebraska, USA). To minimise interference from moisture vapour and CO_2 on N_2O measurement, a precolumn filled with sodium hydroxide coated silica was installed ahead of the analytical column and changed regularly.

The automated system consisted of three sets of four chambers with each set being closed for nine-minute periods, allowing monitoring of one chamber of this set. The sampling sequence was the first chamber of the first set (Chamber 1), the first chamber of the second set (Chamber 5), the first chamber of the third set (Chamber 9), the second chamber of the first set (Chamber 2), and so on. A full measurement cycle for flux determination commenced with lid closure and finished when the lid opened nine minutes later. During this time, the chamber was sequentially sampled at three-minute intervals followed by a known calibration standard (0.5 ppm N_2O, 690 ppm CH_4, 5200 ppm CO_2, Air Liquide Australia). This provided three sampling points per chamber over a nine-minute period once every three hours, allowing eight flux measurements for each chamber to be obtained per day, or 24 per treatments per day. Samples passed through the 3 ml sample loop of two separate (ECD, FID) eight port valves before injection into the respective carrier streams. The LI-820 was connected to the waste vent of one valve and logged at 1 Hz.

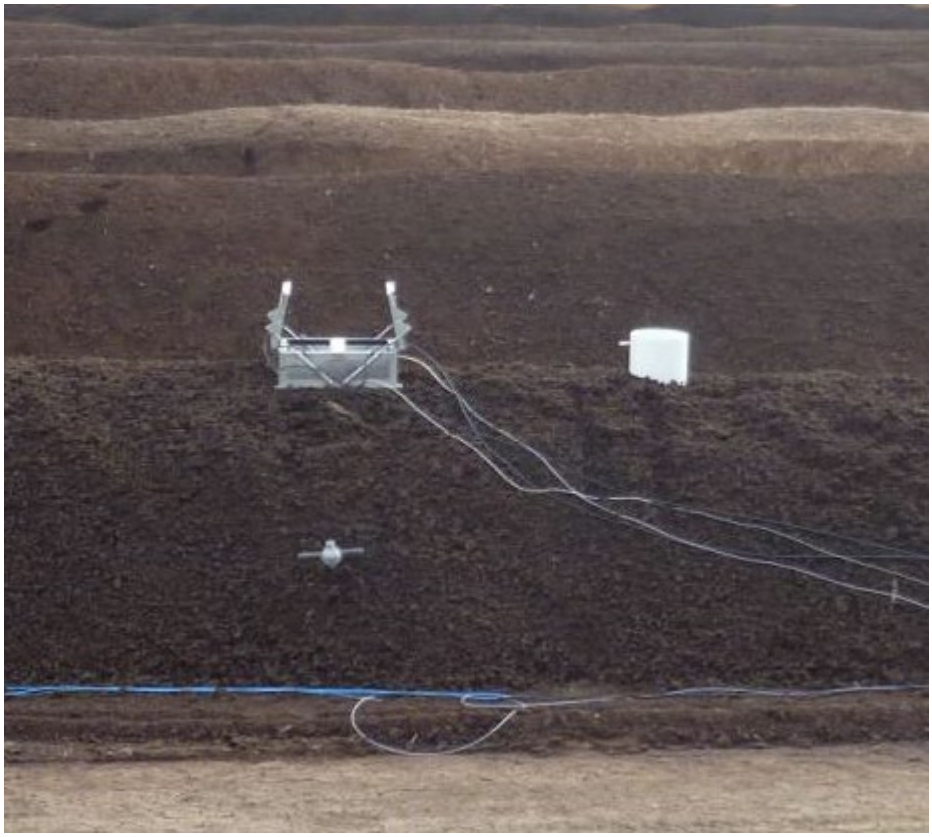


Figure 8 Automated (left) and manual (right) gas sampling chambers

2.9 Calculating gas fluxes

2.9.1 Ammonia

Gas fluxes were calculated in the following way.

Laboratory analysis provided ammonium nitrogen (NH_4-N) concentrations (mg/L) in 0.4 L sulfuric acid samples representing emissions from the chamber surface area over a 20-minute period. Consequently, the hourly ammonia (NH_3) flux rate per square metre was calculated as follows:

$$FR_1 = \frac{C_{NH4\text{-}N} \cdot F_1 \cdot F_2 \cdot V_a \cdot 3}{A_{Ch} \cdot 10^3}$$

(Eq. 2)

Where:

	FR_1:	Hourly NH_3 flux rate per square metre [g NH_3/m^2]
	$C_{NH4\text{-}N}$:	Recorded concentration NH_4-N [ppm = mg/L]
	F_1:	Factor to convert NH_4-N to NH_4 [1.2878]
	F_2:	Factor to convert NH_4 to NH_3 [0.9441]
	V_a:	Volume of acid [L]
	A_{ch}:	Basal area of the measuring chamber [m^2]
	3:	Converts sampling time (20 min) to 1 hour
	10^3:	Converts mg to g

2.9.2 Greenhouse gases and carbon dioxide

Gas fluxes were calculated in the following way.

The flux rate F was calculated using Equation 2. All flux rates were corrected for ambient air temperature during measurement (Equation 3), and expressed on an elemental weight basis as [µg CH_4-C m^{-2} hr^{-1}] for CH_4, [µg N_2O-N m^{-2} hr^{-1}] for N_2O, and [mg CO_2-C m^{-2} hr^{-1}] for CO_2.

$$FR_2 = \frac{b \cdot V_{CH} \cdot MW \cdot 60 \cdot 10^6}{A_{CH} \cdot MV_{corr} \cdot 10^6}$$

(Eq. 3)

Where:

FR_2:	Hourly gas flux rate per square metre [µg/mg gas m^{-2} hr^{-1}]
A_{CH} :	Basal area of the measuring chamber [m^2]
b :	Increase in headspace concentration [ppm min^{-1}]
MW_{N_2O-N} :	Molecular weight of N-N_2O [28 g mol^{-1}]
MW_{CH_4-C} :	Molecular weight of C-CH_4 [12 g mol^{-1}]
MW_{CO_2-C} :	Molecular weight of C-CO_2 [12 g mol^{-1}]
MV_{corr} :	Temperature corrected molecular volume [m^3 mol^{-1}]
V_{CH} :	Volume of the measuring chamber [m^3]
60 :	Conversion from minutes to hours
10^6	Converts g to µg

$$MV_{corr} = 0.02241 \cdot \left(\frac{273.15 + T}{273.15} \right)$$

(Eq. 4)

Where:

MV_{corr} :	Temperature corrected molecular volume [m^3 mol^{-1}]
0.02241 m^3 :	is 22.41 L mol volume
T :	Air temperature during the measurement [°C]. Ambient air temperature was used rather than the temperature inside the chamber. Air pressure was not corrected as the site was located only 100 metres above sea level.

Values expressed in [µg m^{-2} hr^{-1}] were multiplied by 24 to convert flux rates per hour to flux rates per day. Flux rates were converted from an elemental to a molecular weight basis by multiplying obtained results with the following factors:

CH_4-C → CH_4	16/12 = 1.33
N_2O-N → N_2O	44/28 = 1.57
CO_2-C → CO_2	44/12 = 3.67

2.10 Gas fluxes per pile/windrow

Flux rates per square metre and day were calculated for each of the 12 automated and manual flux chambers for each sampling event. Ammonia 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 for the Stockpile and each windrow were calculated by multiplying emissions per square metre per day by the emission surface area (flat top surface area of the Stockpile and windrows), which was determined after establishment and after each turning of the windrows (see Appendix). Emissions per wet tonne of manure and composting mix were calculated by setting cumulated emissions in relation to the original mass of manure or composting mix.

The placement of flux chambers only on top of the windrow is justified by emission measurements at large windrows (shredded vegetation residues) that have shown that 100% of methane and 91% of nitrous oxide is emitted via the top of the row (Andersen et al. 2010).

3 Results

3.1 Temperature profiles

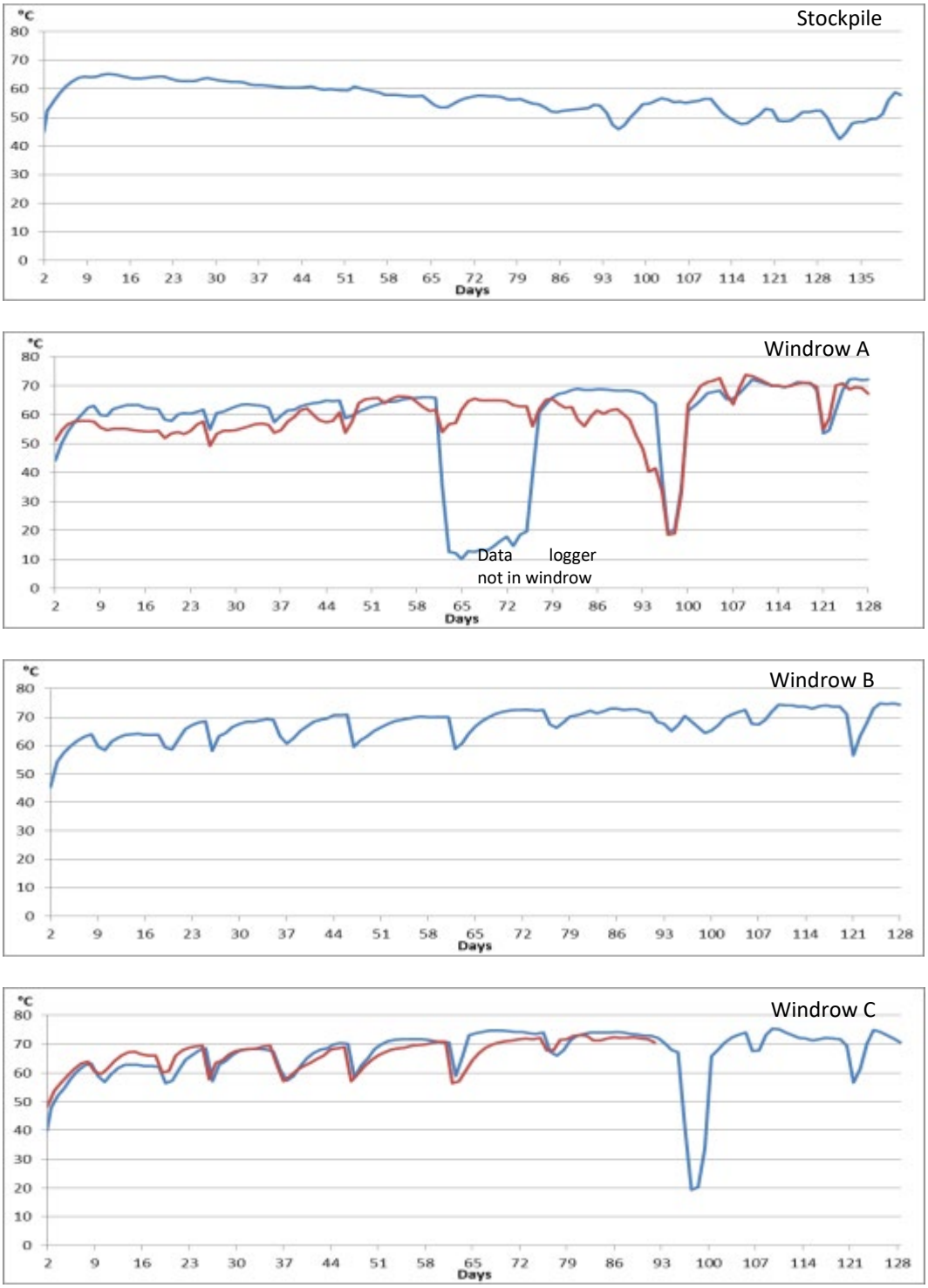
Figure 9 shows the temperature profiles observed inside the stockpiled and composted manure. Abrupt drops in windrow temperatures, which are followed by equally abrupt increases to similar values, indicate that the windrow was turned, an activity during which the data loggers were removed and exposed to ambient temperatures. It can be seen that the windrows were turned ten times during the trial period. One temperature data logger in Windrow A was not placed back in the windrow, which is why ambient temperatures were recorded for a period of about 15 days.

Contrary to previous trials where Stockpile temperatures increased slowly and did not reach 50°C throughout the trial period, Stockpile temperatures in this trial rose very quickly, reached 60°C within four days, and showed maximum temperatures of around 65°C. In fact, temperature profiles in the Stockpile and the three windrows did not vary greatly during the first four weeks of the trial, mostly oscillating between 60°C and 65°C, with temperatures in Windrow C being slightly higher. Subsequently, temperatures in the Stockpile slowly declined to around 50°C over the next two months, and then oscillated around this level for the remainder of the trial period. The rise in temperature of almost 10°C at the very end of the trial period was caused by rain that penetrated into the Stockpile through deep surface cracks that had developed as the manure had dried.

Temperatures in Windrows B and C oscillated between 60°C and 70°C but frequently exceeded 70°C during the second half of the monitoring period. At the end of the trial, after four months of composting, temperatures in all three windrows still exceeded 70°C, indicating ongoing high levels of microbial degradation of organic compounds and heat trapping that results in elevated temperatures inside the windrows. This effect was probably exacerbated by the ongoing addition of piggery effluent, adding nitrogen and readily available carbon.

Maximum temperatures in one section of Windrow A (the red line in Figure 9) reached only around 55°C during the initial five-week composting period. This section had received less sawdust than the remainder of Windrow A. It might be possible that higher ammonia concentrations in this section resulted in suppressed catabolic activity and lower energy release form organic matter degradation (Kuok et al. 2013).

It is worth noting that temperatures dropped below 45°C to 50°C only in the Stockpile during the last four weeks of the monitoring period, and for a one-week period (93-100 days after establishment (DAE)) in Windrow A prior to turning and adding of water. This temperature range is considered to be a threshold below which N_2O emissions from compost piles can increase markedly.



Note: One data logger was used in the Stockpile and Windrow B, and two in Windrows A and C

Figure 9 Daily average temperatures measured inside the Stockpile and windrows during the four-month trial period

3.2 Material characteristics

Table 5 shows the key chemical characteristics of the chicken manure that was subsequently stockpiled or blended with sawdust and composted. The raw manure had nutrient levels that were within the range reported elsewhere (Wiedeman et al. 2008), with high total nitrogen (6.99%) and ammonium (8,711 mg kg^{-1}), but modest organic carbon (18.6%) levels, resulting in a C:N ratio of 2.65. High moisture content (above 50%) and high bulk density (approx. 600 g L^{-1}) prevents layer chicken manure from being composted on its own. The low C:N ratio and high pH (8.5) in the raw manure are precursors for elevated nitrogen losses during composting of the manure, which is why it is usually blended with sawdust or other sources of available carbon, such as wood chip, rice hulls or spoilt hay/straw. Increasing quantities of sawdust were added to the manure in the presented trial to assess the effect that this has on compost characteristics and gaseous emissions. Table 5 shows a time sequence of key chemical characteristics determined during four months of composting layer chicken manure with a low (Windrow A), medium (Windrow B) and high (Windrow C) addition of sawdust. Furthermore, the table also shows the characteristics of manure that had been stockpiled for over five months.

Various key material characteristics changed during the composting process, as shown in Table 5 and Figure 10. Total phosphorous concentrations increased by about 23% for Windrow A and more than doubled in Windrows B and C. Conversely, total nitrogen levels decreased by approximately 39% in Windrow A, 27% in Windrow B and 10% in Windrow C. Ammonium (NH_4-N) concentrations also fell significantly during the composting process, but were still very high compared to nitrate (NO_3-N) concentrations in all windrows. Organic carbon levels decreased by between 21% and 26%, resulting in C:N ratios of 4.59, 10.03 and 11.18 for Windrows A, B and C, respectively (Figure 10). Please note that the C:N ratios displayed in Table 5 and Figure 10 are based on Kjeldahl N and organic carbon measurements, while the C:N ratio used for determining the mixing ratio of manure and sawdust at the outset of the trial (see Section 2.3) are based on carbon and nitrogen levels determined with the Dumas method (University of California Davis 2010). This method was used to determine the C:N ratios of sample material at the beginning and end of the trial. The obtained results (Table 4) confirm the marked decline in both nitrogen and carbon levels during composting for Windrows A, B and C. Furthermore, the results also showed that, at the beginning of the trial, C:N ratios for Windrows A and B were close to the target level of 7 and 14, respectively, while the C:N ratio for Windrow C was lower than the intended value of 21.

Table 4 Values for nitrogen, carbon and C:N ratio determined in raw and composted layer chicken manure with the Dumas method at the beginning and end of the trial period

Material	Dumas N (% DM)		Dumas C (% DM)		C:N Ratio	
	Start	End	Start	End	Start	End
Manure*	5.7	6.1	28.4	28.9	4.97	4.76
Windrow A	5.0	2.5	33.4	23.5	6.74	9.33
Windrow B	3.0	2.3	43.0	31.9	14.4	13.98
Windrow C	2.4	1.8	42.1	29.3	17.35	16.18

* End for manure means values for 'Stockpile'.

Table 5 Changes in key chemical characteristics during stockpiling and composting of layer chicken manure

Manure Management	Date	pH	NH_4-N	NO_3-N	Avail P[#]	Total N*	Total P*	Org C	C:N Ratio^	Moist
			mg/kg DM			% DM				% FM
Raw manure	19/05/17	8.5	8,711	0.89	2,175	6.99	1.52	18.6	2.65	44.0
Windrow A	19/05/17	7.6	13,926	1.90	2,675	6.60	1.45	23.5	3.56	47.3
	26/05/17	8.2	19,652	1.87	2,850	6.05	1.39	21.6	3.58	46.6
	5/06/17	8.2	17,331	2.60	2,475	6.20	1.42	19.8	3.19	42.3
	22/06/17	8.3	14,889	2.91	2,850	4.54	1.42	20.0	4.40	39.9
	3/07/17	8.2	14,707	4.28	2,750	5.00	1.42	20.4	4.08	38.2
	11/08/17	8.4	6,637	21.87	3,150	3.33	1.49	20.9	6.26	25.0
	24/08/17	8.6	6,070	0.73	3,500	3.49	1.81	18.9	5.41	31.5
	31/08/17	8.6	5,476	2.07	4,000	4.00	1.61	18.2	4.56	27.7
	15/09/17	8.6	4,495	1.31	3,950	4.04	1.77	18.5	4.59	23.5
Windrow B	19/05/17	7.4	8,757	0.90	2,100	3.03	0.71	29.8	9.81	44.4
	26/05/17	8.2	10,162	0.98	1,750	3.12	0.79	29.9	9.58	39.0
	5/06/17	8.3	9,687	1.55	1,850	3.05	0.77	27.4	8.99	35.5
	22/06/17	8.4	10,713	5.31	2,300	3.10	1.04	23.1	7.43	40.7
	3/07/17	8.4	10,827	2.18	2,300	3.13	0.97	22.8	7.27	45.1
	11/08/17	8.8	4,551	4.48	3,263	2.37	1.20	21.9	9.23	33.0
	24/08/17	8.9	4,185	1.61	3,225	2.37	1.16	21.5	9.07	37.9
	31/08/17	8.9	3,791	1.55	3,250	2.32	1.43	20.0	8.62	35.4
	15/09/17	8.7	2,821	0.71	3,750	2.20	1.48	22.1	10.03	29.5
Windrow C	19/05/17	7.2	4,984	0.80	1,225	2.65	0.53	33.8	12.76	37.8
	26/05/17	7.7	5,285	0.91	1,500	2.57	0.58	33.8	13.12	33.8
	5/06/17	7.9	5,474	0.75	1,475	2.85	0.80	32.5	11.38	33.5
	22/06/17	8.3	6,184	0.84	1,625	2.54	0.70	27.9	10.96	40.2
	3/07/17	8.0	9,744	1.18	1,250	2.75	0.72	30.1	10.97	49.3
	11/08/17	8.6	4,571	7.50	2,000	2.38	1.03	25.7	10.81	33.3
	24/08/17	8.8	4,539	0.85	1,950	2.26	0.98	26.4	11.68	41.2
	31/08/17	8.7	3,909	26.87	2,150	2.08	0.88	24.8	11.91	38.6
	15/09/17	8.7	3,529	1.47	1,875	2.39	1.20	26.8	11.18	32.0
Stockpile	3/11/17	8.3	13,274	197.49	1,600	5.99	1.36	18.0	3.01	32.2

[#] Colwell – P.
* Kjeldahl analysis.
^ based on values of Kjeldahl N and organic carbon.

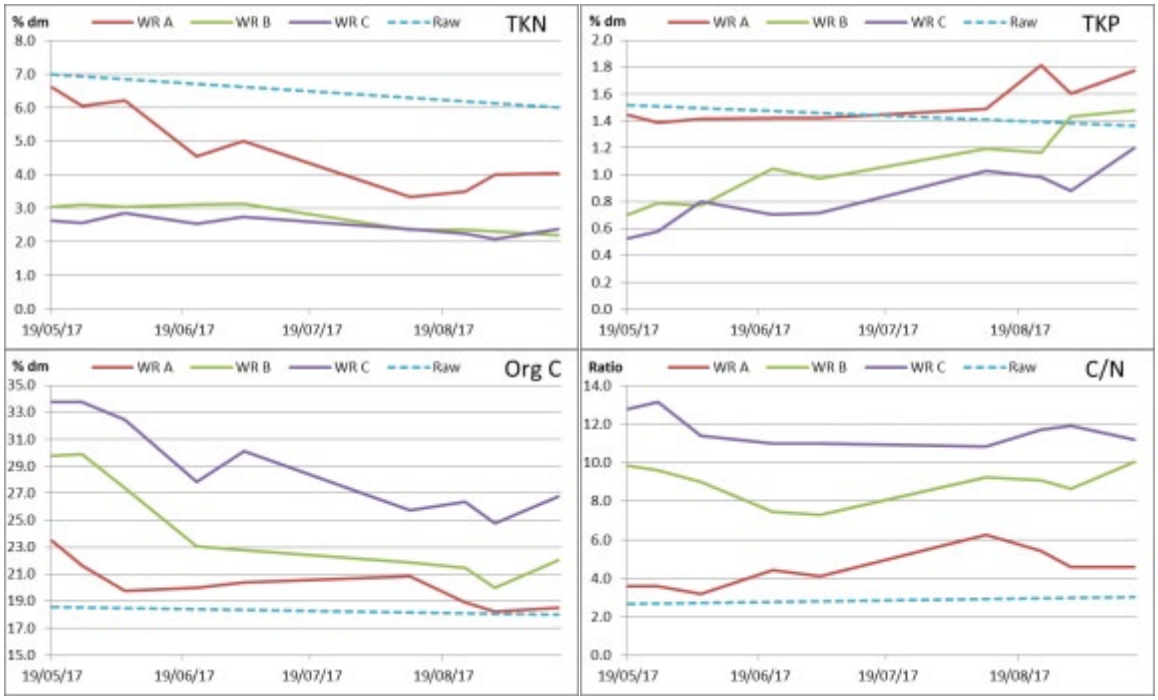


Figure 10 **Changes in total nitrogen (TKN), total phosphorous (TKP), organic carbon (Org C) and the C:N ratio (C:N) during windrow composting (WR A, WR B, WR C) and stockpiling (Raw) of layer chicken manure**

The stockpiled chicken manure dried out progressively on the surface to a depth of 40-50 cm, and formed deep rifts (Figure 11), while it retained high moisture level at the base. Previous trials have shown that not only moisture but also NH_4 and total N levels were significantly higher in the wet base layer of the Stockpile than in the dry top section, suggesting that substantial nitrogen losses had occurred form the dried manure. However, in this instance only an aggregate sample of wet and dry stockpiled manure was analysed, assuming that results represent average values for the whole Stockpile.



Figure 11 **Dried surface of stockpiled chicken manure**

3.3 Greenhouse gas emissions

The greenhouse gases methane (CH_4) and nitrous oxide (N_2O) were determined with an automated sampling system and *in situ* gas analysis, with flux chambers being located on the stockpiled and composted chicken manure.

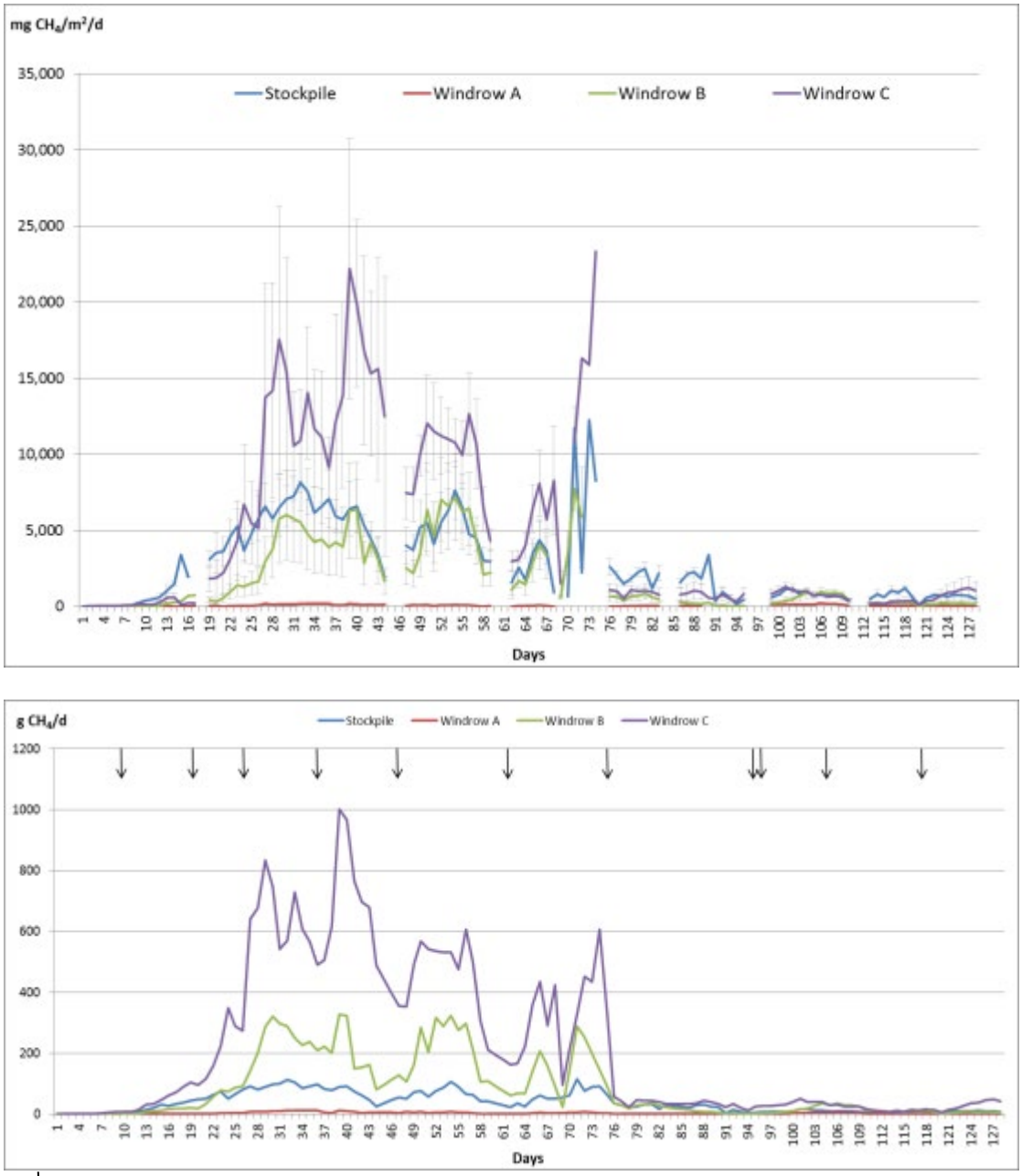
3.3.1 Methane

Daily methane emission rates showed great temporal and spatial variation and also marked differences between treatments (Figure 12). Spatial variation within treatments was greatest within Windrow A and Windrow B. Daily emissions per square metre were consistently low for Windrow A and highest for Windrow C for much of the monitoring period. The highest peaks were detected for Windrow C with emissions ranging between 12,000 and 22,000 mg CH_4 m^{-2} d^{-1}. Peaks in the Stockpile and Windrow B ranged between about 5,000 and 12,000 mg CH_4 m^{-2} d^{-1}. Methane emissions started to increase markedly after a lag phase that lasted for the first ten days after establishment (DAE). Elevated emissions were observed between 20 and 75 DAE. The sudden drop of emissions around 75 DAE, or rather their failure to increase again after the windrows were turned 76 DAE, cannot be explained. The fact that windrows were drying out during that period and aerobic conditions might have prevailed after turning could have been a factor in this, but as low emission values were also observed for the Stockpile this indicates that the most likely cause for this phenomenon was malfunctioning analytical equipment. The consequence of this is that actual cumulated methane emission values for the entire trial period were higher than those presented here.

Average cumulated methane emissions per square metre over the trial period ranged from 7.3 g for Windrow A to 561.1 g for Windrow C, with intermediary levels observed for Windrow B (211.0 g) and the Stockpile (346.2 g). Total cumulated emissions for the Stockpile and the three windrows showed the following results:

Windrow A: 0.40 kg CH_4
Stockpile: 4.80 kg CH_4
Windrow B: 10.50 kg CH_4
Windrow C: 27.40 kg CH_4

Methane emissions are primarily governed by the availability of easily degradable organic compounds, the presence of methanogenic bacteria and the lack or inadequate supply of oxygen, i.e. anaerobic conditions. Anaerobic conditions in the composting and stockpiling of organic materials are commonly associated with high moisture contents and materials that have low air-filled porosity, which usually means high bulk density. This means that the Stockpile and Windrow A could be expected to show the highest and Windrows B and C the lowest emission rates. Yet the reverse was observed, Windrow C showed the highest methane emissions (561.1 g CH_4 m^{-2}), and Windrow A showed the lowest level (7.3 g CH_4 m^{-2}). It is suspected that high concentrations of free ammonia inside the stockpiled and composted chicken manure inhibited methanogenic bacteria, resulting in relatively low production and emission of methane. It was evident (by smell) that significant quantities of ammonia were emitted from Windrow A for most of the monitoring period, and also from the Stockpile when it was disturbed at the end of the trial period.



↓ turning of windrows, with or without irrigation.

Figure 12 Daily methane emission rates per square metre (top) and for each pile or row (bottom) from stockpiled and composted layer chicken manure

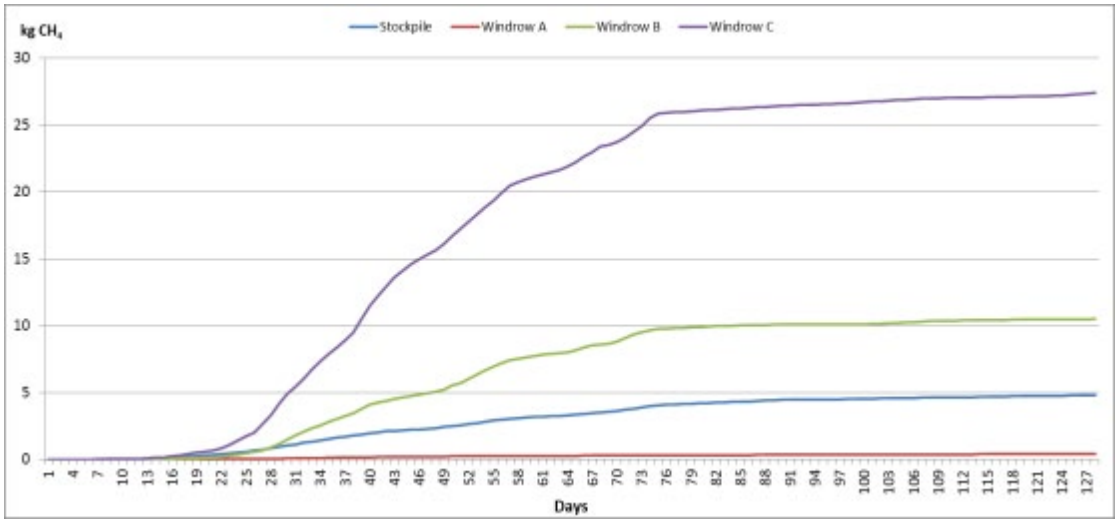


Figure 13 Cumulated methane emissions from stockpiled and composted layer chicken manure

3.3.2 Nitrous oxide

The time series of daily nitrous oxide emission rates in Figure 14 shows consistently low values for the Stockpile and much higher emission rates for all composted materials throughout the monitoring period. During the initial composting period (up to ten DAE), all windrows showed emission peaks that ranged between 300 and 900 mg N_2O m^{-2} d^{-1}, with Windrow B showing the highest peaks. The following period to around 33 DAE saw relatively similar emission rates for the three windrows. Subsequently, however, emissions for Windrow A showed an upward trajectory with peaks ranging between 1,000 and more than 2,500 mg N_2O m^{-2} d^{-1}, while emissions from Windrows B and C remained at similar levels, which were, by and large, below 500 mg N_2O m^{-2} d^{-1}.

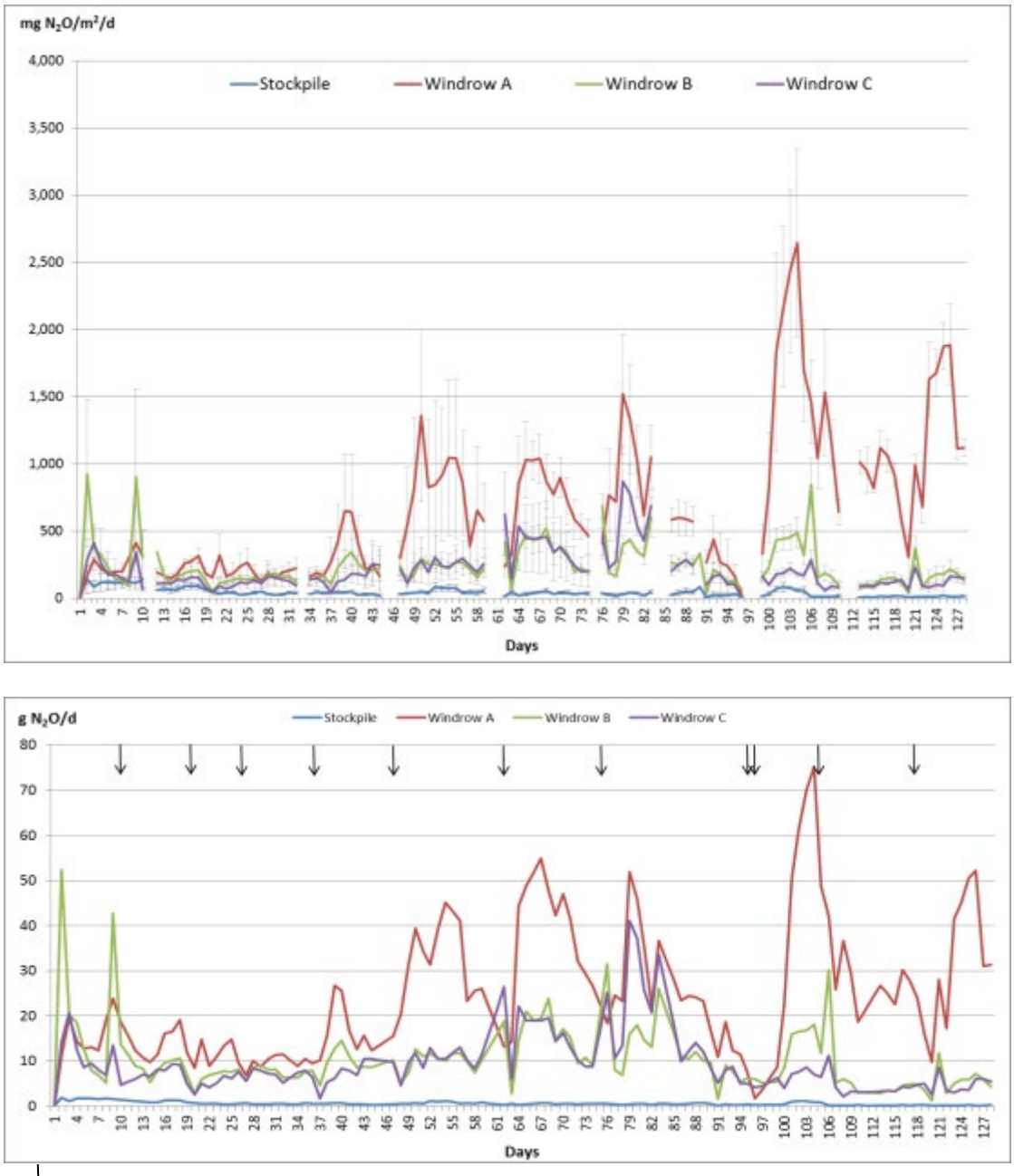
Figure 14 also shows daily emissions for the surface area of the stockpile and windrows, which confirms that, during about 90% of the monitoring period, Windrow A emitted more nitrous oxide than any other treatment. This graph, which also shows when windrows were turned, demonstrates that, starting at 37 DAE, the turning of Windrow A resulted in a sharp increase of nitrous oxide emissions, bar one occasion (106 DAE). This effect was not as obvious for Windrows B and C.

The average cumulated nitrous oxide emissions per square metre over the trial period ranged from 5.6 g for the Stockpile to 82.2 g for Windrow A, with intermediary levels observed for Windrow C (27.2 g) and Windrow B (31.2 g). Total cumulated emissions for the Stockpile and the three windrows showed the following results:

Stockpile: 77.3 g N_2O
Windrow C: 1,240.1 g N_2O
Windrow B: 1,350.0 g N_2O
Windrow A: 3,100.2 g N_2O

The emission of nitrous oxide from organic residues is primarily dependent on the extent to which ammonium is being converted to nitrate. As mineral nitrogen in raw manures is predominantly in the form of ammonium, nitrous oxide emissions from raw and fresh manures tend to be low. In the composting process, transformation of ammonium into nitrate by means of autotrophic nitrification is strongly inhibited in the early stages of composting by high temperatures, high pH and high ammonia concentrations (Insam & de Bertoldi 2007). However, ammonium is converted into nitrate

towards the end of the composting process when conditions for nitrifying bacteria become more favourable, i.e. when ammonia has disappeared and temperatures have declined to below 45°C (Bacheley et al. 2008). For nitrous oxide to be emitted from manure, Spellman and Whiting (2007) suggest that manure first has to be handled aerobically (dry) and then anaerobically (wet). These conditions might have occurred as the windrows became dry between 75 and 95 DAE, and then were re-wetted. However, our records show that temperature does not have to be low (< 45-50°C) for elevated N_2O emissions to occur. Temperatures ranged between 60°C and 70°C when peak emissions from Windrow A were detected.



↓ turning of windrows, with or without irrigation.

Figure 14 Daily nitrous oxide emission rates per square metre (top) and for each pile or row (bottom) from stockpiled and composted layer chicken manure

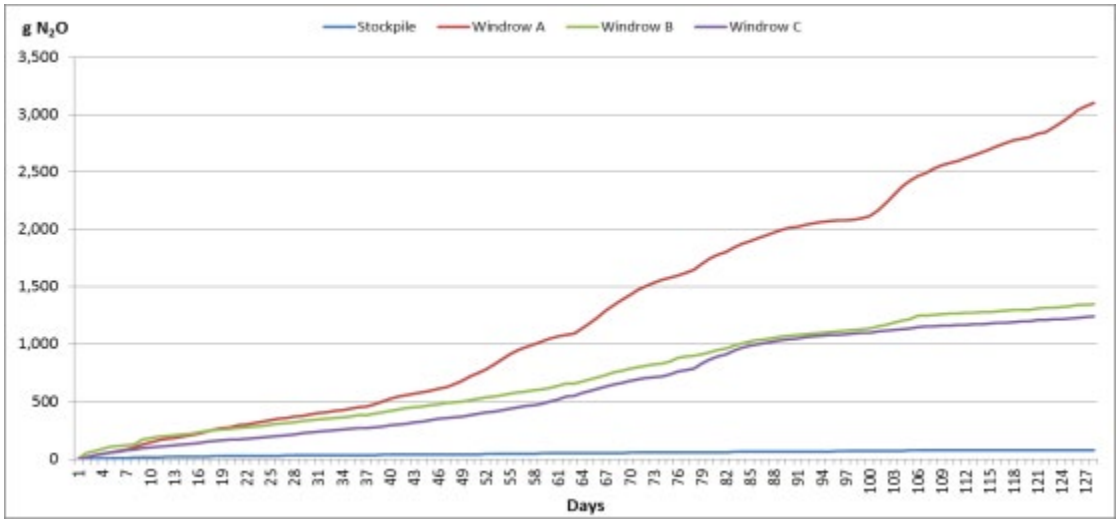


Figure 15 Cumulated nitrous oxide emissions from stockpiled and composted layer chicken manure

3.3.3 Ammonia

Observed daily ammonia emission rates fluctuated between approximately 10 and 50 g NH_3 per square metre for all treatments, except for the Stockpile, which consistently emitted less than 10 g NH_3 per square metre per day after about 20 days of stockpiling (Figure 16). Generally speaking, emission intensity declined after about 65 DAE, and this might be associated with relatively low moisture content towards the end of the composting process. Windrow A and Windrow B showed the highest ammonia losses during the initial composting period (to 20 DAE) before Windrows B and C took over as dominant emitters to about 72 DAE, while emission intensity varied for the remainder of the composting period.

However, ammonia emissions for the entire Stockpile and for whole windrows showed that emissions for all treatments were highest during the first three weeks after establishment. Furthermore, it became more obvious that daily emissions increased in the following sequence:

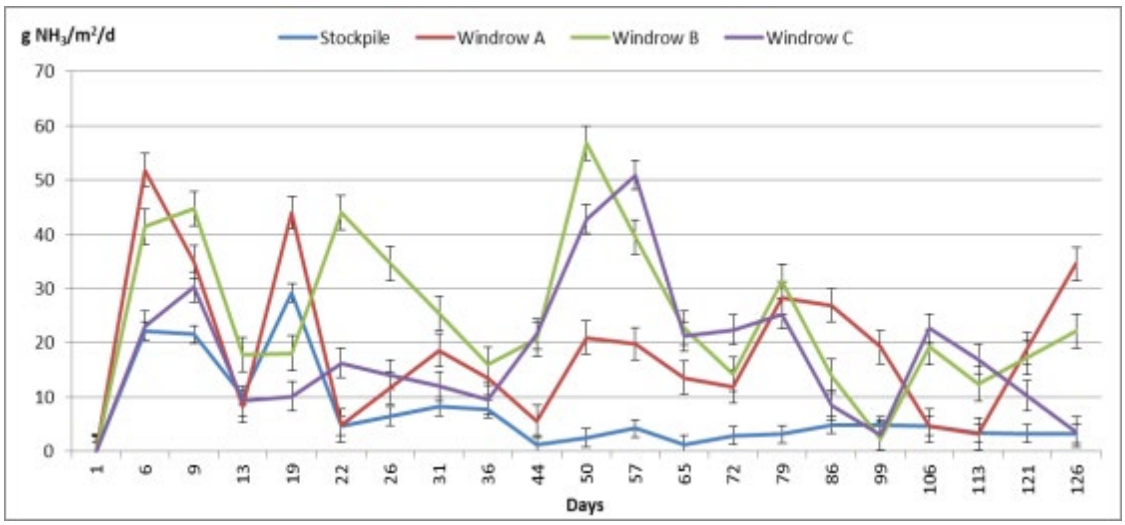
Stockpile < Windrow A < Windrow B < Windrow C.

Average cumulated ammonia emissions per square metre over the trial period ranged from 782 g for the Stockpile to 2,947 g for Windrow B, with emissions of over 2,300 g m^{-2} for Windrows A and C. Total cumulated emissions for the Stockpile and the three windrows showed the following results:

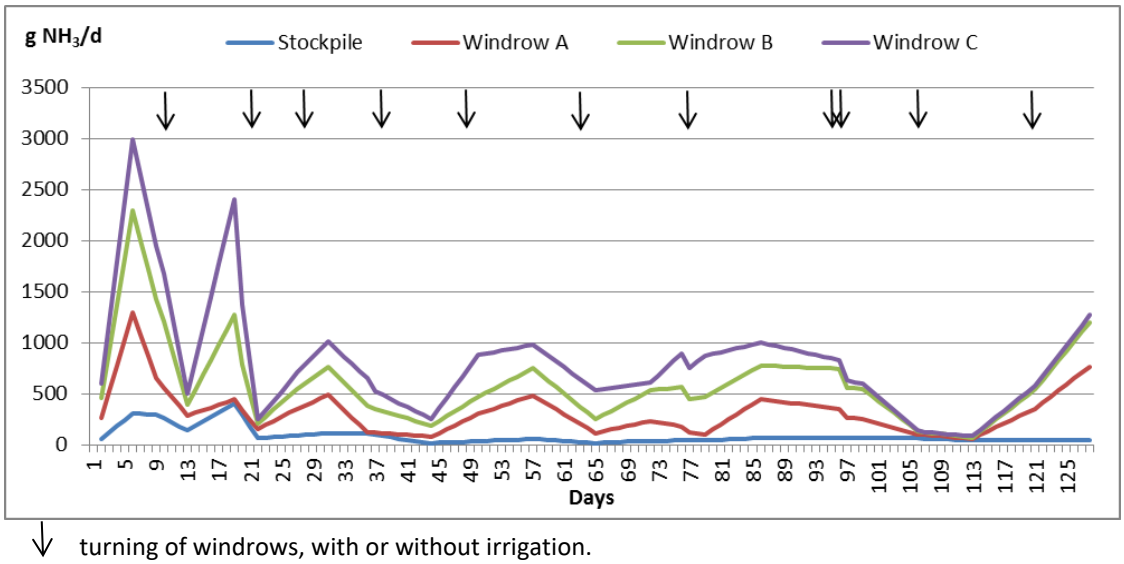
Stockpile: 10.9 kg NH_3
Windrow C: 39.8 kg NH_3
Windrow B: 74.4 kg NH_3
Windrow A: 101.7 kg NH_3

The graph showing cumulated ammonia emissions over the trial period (Figure 17), suggests that, apart from the initial composting period (up to 20 DAE) and the period after rewetting the windrows (103 – 120 DAE), ammonia emission rates were relatively constant and distinctly different for the Stockpile and each of the three windrows. Daily emissions during this 83-day period from the entire Stockpile and the whole windrows amounted to:

50.9 g/d	for the Stockpile (R^2 = 0.9735)
260.2 g/d	for Windrow A (R^2 = 0.9919)
506.5 g/d	for Windrow B (R^2 = 0.9903)
734.8 g/d	for Windrow C (R^2 = 0.9950)



Note: Error bars represent standard error values.



↓ turning of windrows, with or without irrigation.

Figure 16 Daily ammonia emission rates per square metre (top) and for each pile or row (bottom) from stockpiled and composted layer chicken manure

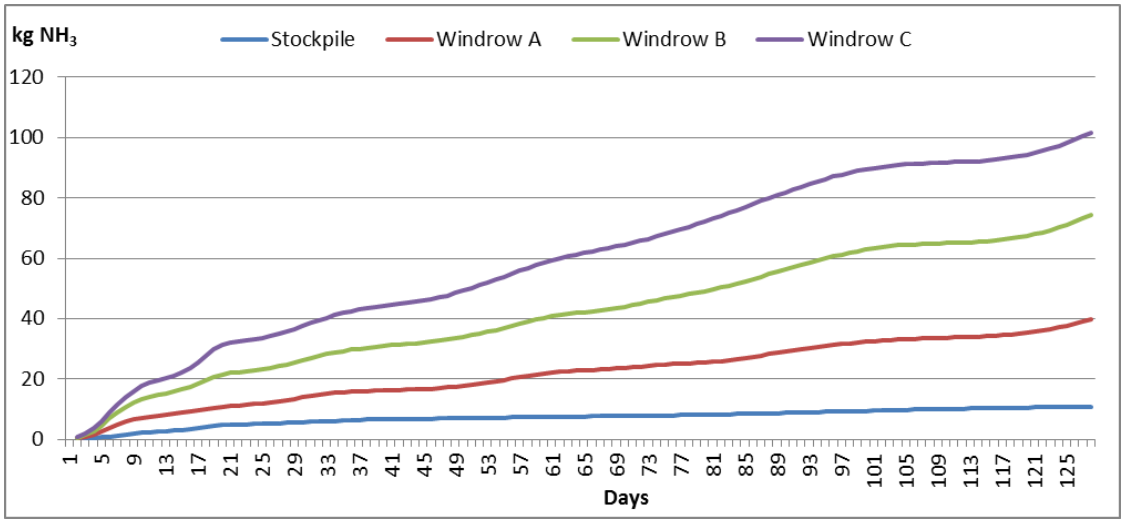


Figure 17 Cumulated ammonia emissions from stockpiled and composted layer chicken manure

3.3.4 Emissions per tonne manure/feedstock

All of the above emission values were expressed per unit surface area (m^2) or for the entire Stockpile or windrow. In order to provide more meaningful data that can be linked to manure quantities and compared with other emission data for organic residues, Table 6 presents emission values per tonne (t) wet and dry manure, and also per tonne wet and dry composting feedstock (i.e. manure plus sawdust). Methane emissions per tonne manure and feedstock were markedly lower for Windrow A (4.2 g-10.25 g CH_4 t^{-1}) than for all other treatments. The Stockpile (187 g-422 g CH_4 t^{-1}) and Windrow B (154 g-513 g CH_4 t^{-1}) showed similar methane emission levels, while emissions from Windrow C (470 g-2,063 g CH_4 t^{-1}) were highest for each category. As far as nitrous oxide is concerned, the Stockpile showed markedly lower emissions (3.0 g-6.8 g N_2O t^{-1}) than the three windrows, which emitted between 19.8 g and 79.7 g N_2O t^{-1}, with Windrow B showing the lowest value among windrows for each category. Ammonia emissions from the Stockpile and Windrow A were relatively similar and showed the lowest values in each category. Windrow C consistently showed the highest ammonia emission values.

Table 6 Combined gas emissions per tonne wet/dry manure and per tonne wet/dry feedstock

Manure management	Emissions (g)			Emissions as CO_2-e (kg)			
	CH_4	N_2O	NH_3	CH_4	N_2O	NH_3*	Total
per tonne wet manure							
Stockpiling	186.89	3.00	422.31	4.67	0.90	1.63	7.19
Windrow A	4.54	35.29	453.19	0.11	10.52	1.75	12.38
Windrow B	227.13	29.21	1,610.47	5.68	8.71	6.20	20.59
Windrow C	912.92	41.32	3,390.24	22.82	12.31	13.06	48.19
per tonne dry manure							
Stockpiling	422.24	6.79	954.17	10.56	2.02	3.67	16.25
Windrow A	10.25	79.74	1,023.92	0.26	23.76	3.94	27.96
Windrow B	513.17	66.00	3,638.65	12.83	19.67	14.01	46.51
Windrow C	2,062.62	93.36	7,659.83	51.57	27.82	29.50	108.89
per tonne wet feedstock							
Stockpiling	186.89	3.00	422.31	4.67	0.90	1.63	7.19
Windrow A	4.21	32.74	420.36	0.11	9.76	1.62	11.48
Windrow B	153.87	19.79	1,091.04	3.85	5.90	4.20	13.95
Windrow C	470.01	21.27	1,745.43	11.75	6.34	6.72	24.81
per tonne dry feedstock							
Stockpiling	422.24	6.79	954.17	10.56	2.02	3.67	16.25
Windrow A	9.23	71.76	921.48	0.23	21.39	3.55	25.17
Windrow B	305.88	39.34	2,168.88	7.65	11.72	8.35	27.72
Windrow C	880.95	39.88	3,271.54	22.02	11.88	12.60	46.51

* indirect N_2O emissions following volatilisation of NH_3, calculated according to IPCC 2006a and IPCC 2006b.

Converting methane and nitrous oxide emissions into carbon dioxide equivalents (CO_2-e) allows the addition of different greenhouse gas emissions such as methane and nitrous oxide, and the comparison of emissions from different manure handling systems. This is achieved by multiplying measured methane and nitrous oxide emissions with the global warming potential of these gases, which is 25 for methane and 298 for nitrous oxide (Department of Environment and Energy 2017a). Ammonia is not a greenhouse gas, which is why there is no global warming potential value for ammonia. Yet volatilised ammonia is, over time, deposited on soil and water bodies, where it affects the carbon cycle through increased nutrient supply. The fact that total global ammonia emissions have increased from an estimated pre-industrial value of 11 million tonnes of nitrogen per year to 54 million in 2000, and are projected to increase to 116 million by 2050 (IPCC 2007), demonstrates that ammonia emissions do have a significant global environmental impact and justifies the establishment of a secondary nitrous oxide emission factor for ammonia emissions (IPCC 2006a, IPCC 2006b). The IPCC emission factor of 0.01 kg N_2O-N per kg of emitted NH_3-N has been used to convert ammonia emissions into carbon dioxide equivalents (CO_2-e) in Table 6.

Emission values expressed as carbon dioxide equivalents are also presented in Table 6, and these data show that total GHG emissions (CH_4 + N_2O + NH_3) were lowest for the Stockpile (7.2-16.3 kg CO_2-e t^{-1}), followed by Windrow A (11.5-28.0 kg CO_2-e t^{-1}), Windrow B (14.0-46.5 kg CO_2-e t^{-1}) and Windrow C (24.8-108.9 kg CO_2-e t^{-1}). GHG emissions from the Stockpile were dominated by methane (64.9%) and those from Windrow A by nitrous oxide (85.0%), while emissions from the other two windrows were more balanced, with nitrous oxide (42.3%) being the dominant gas emitted from Windrow B and methane (47.4%) from Windrow C. Ammonia emissions contributed between 14.1% (Windrow A) and 30.1% (Windrow B) to total GHG emissions.

GHG emission results previously obtained as part of the National Agricultural Manure Management Program (*Composting as a Means of Minimising Greenhouse Gas Emissions from the Manure Supply Chain*) were expressed as carbon dioxide equivalents per tonne wet feedstock, and did not account for ammonia emissions. Hence, to facilitate comparison with previous results, emissions that account for only methane and nitrous oxide amounted to the following quantities of CO_2-e per tonne wet feedstock:

Stockpile	5.57 kg
Windrow A	9.87 kg
Windrow B	9.75 kg
Windrow C	18.09 kg

Additional accounting for ammonia emissions as indirect GHG increased CO_2-e emissions per tonne wet feedstock by 29.2%, 16.4%, 43.1% and 37.2% for the Stockpile and Windrows A-C, respectively.

3.4 Mass and nutrient balance for composting

Mass and nutrient balances were carried out on large windrows that were located at a commercial composting operation, employing large-scale equipment for composting and material handling. Therefore, the accuracy of the following mass and nutrient balances might not be high and has to be seen in this light.

3.4.1 Mass balance

The feedstock mass (manure and sawdust) used for establishing each windrow was recorded, as was the mass of finished compost, before and after screening through a 10 mm trommel screen. The resulting mass balance in Table 8 shows that dry matter mass was reduced by only between 15% and 19% during five months of composting. The presented fresh matter yield of screened compost, however, is misleading as moisture content varied between windrows. If it is assumed that all screened compost has 35% moisture, the amount of finished compost would range between 40 t and 57 t fresh matter, representing between 60% and 70% of the original fresh matter feedstock (Table 7).

Table 7 Assumed fresh matter compost yield if moisture content was 35% for all products

	Mass at 35% moisture	Bulk density*	Volume	Yield
	t	kg/m^3	m^3	% FM feedstock
Windrow A	57.02	670	78.87	60.21
Windrow B	42.79	560	77.61	62.73
Windrow C	40.67	470	93.70	69.71

* Determined for compost at 'as is' moisture content at time of screening.

Table 8 **Fresh matter (FM) and dry matter (DM) mass balance (t) for composting of layer chicken manure with addition of varying quantities of sawdust**

	Feedstock						Compost					
	Manure		Sawdust		Total		Unscreened		Screened		Yield (screened, %)	
	FM	DM	FM	DM	FM	DM	FM	DM	FM	DM	FM	DM
Windrow A	87.84	38.87	6.86	4.32	94.70	43.20	56.10	42.92	53.10	37.06	56.07	85.80
Windrow B	46.21	20.45	22.00	13.86	68.21	34.31	45.20	31.87	43.80	27.81	64.21	81.06
Windrow C	30.01	13.28	28.28	17.82	58.29	31.10	45.80	31.14	44.50	26.43	76.34	85.00

Table 9 **Nutrient and carbon balance (kg) for composting of layer chicken manure with addition of varying quantities of sawdust**

Nutrient & Carbon		Windrow A				Windrow B				Windrow C			
		N	P	K	Org C	N	P	K	Org C	N	P	K	Org C
Input	- Feedstock	2,508	662	915	11,381	1,333	350	486	12,203	876	228	319	12,655
	- Irrigation	3	1	14	n.d.	12	3	29	n.d.	16	5	37	n.d.
Output	- Screened compost	1,093	658	831	6,689	558	375	468	6,753	565	287	351	8,509
Loss	- kg	1,417	5	98	4,692	786	-22	47	5,450	328	-54	5	4,146
	- % of input	56.5	0.7	10.6	41.2	58.5	-6.4	9.1	44.7	36.7	-23.2	1.4	32.8

3.4.2 Nutrient and carbon balance

The nutrient and carbon balance for the three windrows is shown in Table 9. The difference between nutrient inputs in feedstock and irrigation water and outputs in screened compost revealed unaccounted losses of potassium (K) that ranged between 1.4% (Windrow C) and 10.6% (Windrow A). Phosphorous (P) losses were observed only for Windrow A (0.7%), while the applied calculations suggest that the phosphorous load in the finished compost was 6.4% and 23.2% higher than in the input materials for Windrow B and Windrow C, respectively. Although phosphorous content (% DM) usually does increase during the composting process in relative terms, the phosphorous load in the material does not increase. Therefore, the increase in phosphorous shown for Windrows B and C are incorrect and have to be seen as within the combined margin of error of (i) carrying out the mass balance on a large, commercial scale, (ii) taking feedstock and effluent samples, and (iii) analysing these samples.

Losses recorded for both nitrogen (N) and carbon (Org C) were significant for all three windrows. Nitrogen losses amounted to 57% and 59% of inputs for Windrow A and Windrow B, respectively, while the loss for Windrow C was markedly lower at only 37%. The amount of organic carbon was reduced by 41% and 45% for Windrows A and B respectively, but only by 33% for Windrow C. The ratio of carbon and nitrogen losses ($C:N_{loss}$) shows values of 3.3, 6.9 and 12.6 for Windrows A, B and C, respectively, reflecting the correlation of C:N ratios of the original feedstock mixes (7:1, 14:1, 21:1). The $C:N_{loss}$ values also reinforce the fact that nitrogen losses are proportionately higher than carbon losses when material with low C:N ratio is composted, and that, in these cases, the C:N ratio tends to increase or remain unchanged during the composting process (Figure 10), rather than decrease as is the case when the composted feedstock has a C:N ratio > 25:1.

Nitrogen losses via ammonia volatilisation determined through ammonia emission measurements estimated losses of 33, 61 and 84 kg for Windrows A, B and C, respectively, which accounts for only 2.3%, 7.8% and 25.5% of the losses determined in the mass balance for Windrows A, B and C, respectively.

3.5 Economic assessment

In the case of Organic Nutrients, the acquisition of feedstock for composting incurs costs of $10/t for layer chicken manure and approximately $60.61/t for sawdust. This price difference is the reason that as little sawdust as possible is used to compost the chicken manure. The significant loss of nitrogen that this practice entails is of little commercial consequence, as the resulting compost still has relatively high nitrogen content, and farmers are reluctant to pay a price for compost that directly reflects its nutrient value.

In order to assess the economic implications of increasing the proportion of sawdust in the feedstock mix, the practices represented in Windrows A, B and C were projected on to the whole composting operation (Operations A, B, and C), assuming annual throughput of 30,000 tpa of layer chicken manure. Comparison of input and output costs, assuming all generated compost is sold for $\$72.00\ t^{-1}$ shows that increasing the amount of sawdust reduces the annual financial surplus by around $50,000 and $125,000 for Operations C and B, respectively (Table 10). Surplus for Operations C and B would match that of Operation A if the sales price for compost would increase from $\$72.00\ t^{-1}$ to $\$73.20\ t^{-1}$ and $\$76.50\ t^{-1}$, respectively. Organic Nutrients is of the opinion that it might be possible to increase prices to $78.00 for compost product originating from Operations B and C. However, a price increase for products generated in Operations B and C might be difficult to realise in agricultural markets, as generated compost would have markedly lower nutrient levels than those currently generated (Operation A). An easier way of realising this goal would be to adopt a volume-

based pricing structure. Due to different bulk densities of compost generated in Operations A, B and C, volumetric yield is increasing more than mass yield as more sawdust is added as bulking material. If the current annual surplus of $960,000 is to be retained for all three operations, volume-based prices would need to be $48.48, $43.19 and $34.77 per cubic metre for Operations A, B and C, respectively.

Table 10 Economic implications of composting chicken manure with different quantities of sawdust

	Unit	Operation A	Operation B	Operation C
Input				
Manure	Quantity (tpa)	30,000	30,000	30,000
	Value ($)	300,000	300,000	300,000
Sawdust	Proportion (% w/w)	7.8	47.6	94.1
	Quantity (tpa)	2,343	14,283	28,224
	Value ($)	141,994	865,614	1,710,518
Output				
Compost	Quantity* (tpa)	19,474	27,779	40,585
	Volume (m^3/a)	28,924	49,224	85,454
	Value# ($)	1,402,161	2,000,103	2,922,119
Surplus	Value ($)	960,168	834,489	911,600
Difference	Value ($)		-125,679	-48,567

* at 35% moisture.

\# at sales price of $72 t^{-1}.

If the current pricing structure remains unchanged and all compost is sold for $72/t, sales revenue would amount to approximately $1.4 million for Operation A, $2.0 million for Operation B and $2.9 million for Operation C. In comparison, the nominal value of major plant nutrients (N, P, K) contained in compost generated in Operations A, B and C amounts to about $2.5 million, $2.6 million and $3.3 million, respectively (Table 11). This demonstrates that compost products particularly from Operation A are undervalued, which is still the case if only 30% of applied nitrogen is considered as becoming plant available. It should be noted that the above valuation does not take into account minor plant nutrients, micronutrients, liming effects, carbon sequestration, and other direct and indirect benefits the use of compost and other organic soil amendments can deliver to users.

Table 11 Annual nutrient load and value in compost generated from layer chicken manure and different quantities of sawdust

	N		P		K		Total
	kg	$*	kg	$*	kg	$*	$
Operation A	373,686	560,529	224,845	1,214,162	283,865	723,855	2,498,546
Operation B	362,784	544,176	243,762	1,316,317	303,800	774,691	2,635,184
Operation C	564,054	846,081	285,995	1,544,372	350,198	893,004	3,283,457

* at value of N = $1.50 kg^{-1}, P = $5.40 kg^{-1} and K = $2.55 kg^{-1}
(*based on farm gate price for bulk single nutrient fertiliser in South East Queensland, autumn 2018*).

If nitrogen is valued at $1.50 kg^{-1}, the amount of nitrogen that is lost in the assessed composting operations represents a monetary loss of close to $730,000, $770,000 and $500,000 annually for Operation A, B and C, respectively.

4 Discussion

4.1 Trial results

Measuring methane, nitrous oxide and ammonia emissions from stockpiled and composted layer chicken manure over a four and a half month period enabled calculation of emission factors, with and without accounting for ammonia emissions, for these manure management options.

Greenhouse gas emissions recorded in this trial were similar to those obtained for stockpiling and composting of layer chicken manure in previous trials (Table 12). Emissions previously recorded for stockpiling and windrow composting amounted to 3.2 kg and 5.6 kg CO_2-e per tonne wet feedstock respectively, while corresponding emissions for Stockpile and Windrow A in this trial showed values of 5.7 kg and 9.9 kg, respectively. These results confirm that stockpiling and composting of layer chicken manure generate relatively low GHG emissions, compared to emissions observed from other manures (Table 12). However, indirect emissions caused by ammonia volatilisation were not accounted for previously. Additional accounting for ammonia volatilisation increased total CO_2-e emissions per tonne wet feedstock in stockpiling and composting by between 16% and 43%. However, Nayler et al. (2016) found that ammonia emissions contributed 97.7% of total GHG emissions from stockpiled layer chicken manure during a 32-day monitoring period. Conversely, their results confirm that methane and nitrous oxide emissions from stockpiled layer chicken manure are low, reportedly amounting to only 0.65 kg CO_2-e per tonne wet manure.

While nitrous oxide was the main contributor (77%-99%) to total GHG emissions from all chicken manure management systems in the previous trial (Table 12), the current trial showed that methane emissions dominated gaseous losses from the Stockpile and Windrow C (Table 6). Data provided by Nayler et al. (2016) showed low nitrous oxide emissions from stockpiled manure and negligible methane emissions.

The main methodologies employed for estimating GHG emissions from soil include using either different types of flux chambers or one of several micrometeorological techniques (Oertel et al. 2016, Rapson & Dacres 2014). There is no single best technique that should be used universally, but the choice of method should be informed by considering applicability (spatial variability, observable area, continuous monitoring, analytical processes), accuracy and precision (bias, e.g. influence on soil structure), and costs and workload involved (Oertel et al. 2016). What was said about methodologies used for measuring GHG emissions from soil is equally applicable to emission measurements from manure or compost piles.

Initial comparative research (on emissions from soil) concluded that results obtained with flux chambers and micrometeorological techniques were similar and comparable (Christensen et al. 1996). Yet, more recent work that compared an advanced micrometeorological technique (single open-path Fourier transform infrared spectrometer deployed in a slant-path configuration) with daily flux chamber sampling on a horticultural field, suggests that micrometeorologically determined N_2O emission are 20% to 40% higher than emissions determined by means of daily flux chamber sampling (Bai et al. 2019).

Measurement of GHG emissions with automated flux chambers and *in situ* analysis, allowing for eight gas concentration measurements per chamber and day, provides results that are superior to those sampled manually once per day or once per week. Therefore, CH_4, N_2O and CO_2 emission results reported for this trial are believed to be adequately robust and do represent valid emission

data. However, this statement does not extend to the period when methane measurements were unusually low (> 75 DAE), possibly due to malfunctioning equipment.

Conversely, weekly gas sampling via flow-through chambers seems not to have been adequate for accurately estimating ammonia emissions. Although the devised sampling and analytical system showed good recovery rates during testing, recovery rates in the field were not satisfactory, and need to be improved. This is particularly pertinent when considering ammonia emission rates from stockpiled layer chicken manure, and the high contribution (97.7%) that ammonia losses make to total GHG emissions reported by Nayler et al. (2016).

Table 12 Greenhouse gas emissions from stockpiling and composting of animal manures

Manure	**Management**	**Emissions as CO_2-e (kg per t wet feedstock)**		
		CH_4	N_2O	Total
Dairy	Stockpiling of Pond Sludge	19.9	31.8	**51.7**
	Stockpiling of Yard Scrapings	2.5	13.9	**16.4**
	Composting	14.2	49.0	**63.2**
Feedlot	Stockpiling	4.1	41.3	**45.4**
	Windrow Composting	2.4	0.1	**2.5**
	Aerated Pile Composting	9.2	0.4	**9.6**
Chicken (Layer)	Stockpiling	0.7	2.5	**3.2**
	Windrow Composting	0.2	5.4	**5.6**
	Aerated Pile Composting	0.1	4.1	**4.2**
Pig (Eco Shelter)	Stockpiling	21.7	13.6	**35.3**
	Windrow Composting	170	2.5	**172.5**

(Source: Rowlings & Biala 2016)

Nitrous oxide emissions from composted organic residues are governed, among others, by mineral nitrogen (ammonium) levels and subsequent nitrification and denitrification processes. As the low C:N ratio of the compost mix, combined with high pH, can result in significant ammonia losses, it was expected that increasing the addition of sawdust (Windrows B and C) would reduce GHG emissions during the composting of layer chicken manure, particularly as nitrous oxide was found to dominate GHG emissions in previous trials (Rowlings & Biala 2016). Characteristics of the blended feedstock mixes (Table 13) were in line with this theory, and gave rise to expectations of lower emissions as the amount of sawdust was increased in Windrows B and C. However, our expectations were unfounded and the theory was not confirmed as measurements showed that total CO_2-e emissions per tonne wet feedstock did not decrease as expected but were in fact similar for Windrows A and B, and approximately twice as high for Windrow C (Table 6).

Table 13 Key characteristics of blended feedstock for composting Windrows A-C

	pH	NH_4-N	Total N*	Org C	C:N Ratio^	Moist	Bulk density
	-	mg/kg DM	% DM	% DM	-	% FM	kg/L
Windrow A	7.6	13,926	6.60	23.5	3.56	47.3	0.64
Windrow B	7.4	8,757	3.03	29.8	9.81	44.4	0.50
Windrow C	7.2	4,984	2.65	33.8	12.76	37.8	0.41

* Kjeldahl analysis.
^ based on values of Kjeldahl N and organic carbon.

Closer scrutiny of measured emissions shows that nitrous oxide emissions did indeed fall as the amount of sawdust increased. However, Table 6 reveals that the observed reduction in nitrous oxide emissions, amounting to 3.86 kg and 3.42 kg CO_2-e per tonne wet feedstock for Windrow B and C respectively, was negated by methane and ammonia emissions that increased by 6.32 kg and 16.74 kg CO_2-e per tonne wet feedstock for Windrow B and C respectively, compared to Windrow A. Methane emissions from Windrow B were 35-fold higher than those from Windrow A, and those from Windrow C were more than 100 times higher than emissions from Windrow A. Ammonia emissions for Windrows B and C were higher than emissions from Windrow A by a factor of 2.6 and 4.2, respectively. Hence, increasing sawdust in the composting mix resulted in a swap of emissions, with nitrous oxide emissions decreasing, but methane and ammonia emissions increasing. Different bulk densities in material composted in Windrows A, B and C throughout the composting process (Table 12, Table 7) may have been contributed to the observed effects as, according to Prado et al. (2015), decreasing bulk density results in decreasing nitrous oxide emissions but increasing ammonia emissions.

The fact that methane emissions from Windrow A were very low even during the initial composting period (37 DAE) when this material had the highest moisture content (Figure 18) and that methane emissions from Windrow C peaked while its moisture content was still below 40% (Figure 18), confirms that factors other than moisture, bulk density (i.e. passive oxygen supply) and size of rows affected methane emissions. Higher volatile solids levels in Windrows B and C than in Windrow A and their subsequent degradation during composting (Figure 18) can partially explain why methane emissions were higher in Windrows B and C than in Windrow A. However, it does not explain why very little methane was emitted from Windrow A, which in fact was less than from the Stockpile.

It is suspected that high concentrations of free ammonia particularly inside the Stockpile and Windrow A inhibited methanogenic bacteria, resulting in relatively low production and emission of methane. This effect has been investigated rarely within a composting context (Kuok et al. 2013), but the inhibitory effects of ammonia on methanogenic bacteria and methane generation is very well established in the field of anaerobic digestion (Yenigün & Demirel 2013). Sensory observations (smell) indicated that significant quantities of ammonia were emitted from Windrow A for most of the monitoring period, and also from the Stockpile when it was disturbed at the end of the trial period.

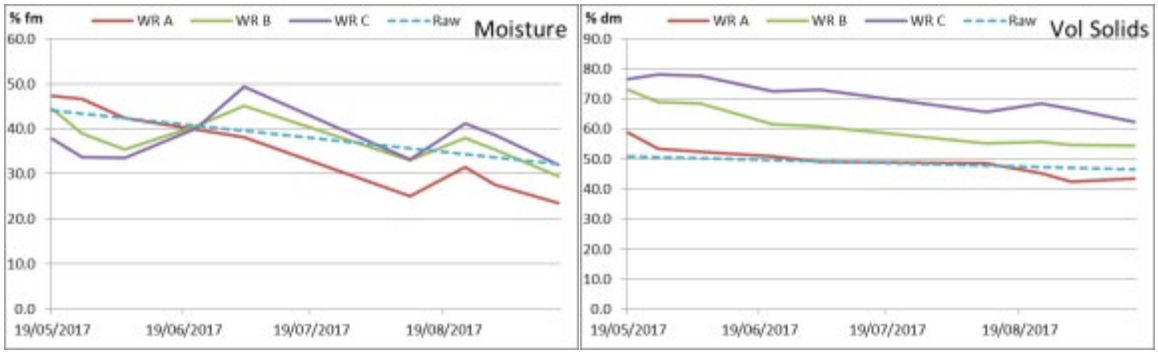


Figure 18 Changes in moisture and volatile solids levels during composting (WR A, WR B, WR C) and stockpiling (Raw) of chicken manure

Loss of dry matter during the composting process ranged between 15% and 19%. These figures are low compared to dry matter loss of around 50% after 80 to 100 days of composting manure solids (Inbar 1989). One reason for relatively low dry matter degradation during the described trial could be that the manure was amended with cypress sawdust, which has a relatively high lignin content of more than 30% (Okino et al. 2010). Lignin, however, is virtually not degraded during composting (Inbar 1989), which is why cypress sawdust provides little available carbon to bind excess nitrogen during composting and is relatively ineffective in reducing nitrogen losses via ammonia volatilisation. Other carbon-rich bulking materials with low lignin and high degradable carbon (cellulose and hemicellulose) contents would be a better choice for co-composting layer chicken manure and achieving reduced ammonia volatilisation losses.

The nutrient balance showed modest potassium losses (1.4% to 10.6%) and a modest phosphorous loss (0.7%) was also calculated for Windrow A. However, compost generated in Windrows B and C contained 6.4% and 23.2% more phosphorous than was added in the input materials, respectively. Such an increase in phosphorous is impossible, and has to be seen as within the margin of error of carrying out the mass balance on a large, commercial scale composting operation.

Calculated nitrogen losses amounted to 57% and 59% of inputs for Windrow A and Windrow B, respectively. The loss for Windrow C was markedly lower at 37%, which is, however, still a significant loss in its own right. These losses are within the range of what has been reported elsewhere (e.g. Karlen et al. 2002, Michel et al. 2004, Peigné & Girardin 2004; Jiang et al. 2011), yet well above the mean total nitrogen losses (36%) observed from poultry manure management, which was reported by Pardo et al. (2015) as result of a meta-analysis of gaseous emissions from organic waste management. The same meta-analysis showed that 1.3% of total nitrogen input was lost as nitrous oxide, and 16.7% as ammonia. Losses in this study were much lower, amounting to between 0.06% and 0.09% of total nitrogen input for nitrous oxide, and ammonia emissions represent 1.3%, 4.6% and 9.4% of total input nitrogen for Windrows A, B and C, respectively. However, the quoted meta-analysis data (Pardo et al. 2015) represent all poultry manures and a range of manure management options, so that the meta-analysis figures are not directly comparable to our results, which only represent composting of layer chicken manure.

Ammonia emissions accounted for 2.3%, 7.8% and 25.5% of the calculated total nitrogen losses for Windrows A, B and C, respectively, and nitrous oxide losses made up 0.14%, 0.11%, 0.24% for Windrows A, B and C, respectively.

The economic analysis suggests that current nitrogen losses at the Organic Nutrient operation amount to about $730,000 per annum. Yet reduction of nitrogen losses by increasing the proportion of sawdust in the composting feedstock cannot be achieved easily due to different feedstock prices. The increased use of sawdust reduces the operation's financial surplus if the current weight-based

pricing structure is maintained. This dilemma can be overcome by (i) increasing the sales price by $1.20 to $4.50 per tonne, (ii) changing the pricing structure from weight-based to volume-based, or (iii) substituting sawdust at least in part with cheaper bulking material such as shredded clean vegetation residues. As increased use of sawdust results in lower N, P, K concentrations in generated compost, it might be difficult to realise higher sales prices in agricultural markets. This is despite the fact that agricultural markets seem to undervalue compost products, even if only nitrogen, phosphorous and potassium are considered. However, compost products with higher sawdust content could be used for the production of growing media and potting mixes, where it should be easier to realise higher prices. This might be necessary as co-composting of chicken manure with more sawdust would require a larger composting pad and more material handling, aspects that were not considered in the economic assessment.

4.2 Determination of emission factors

Although composting is now a recognised management system for agricultural manures, the employed methodology renders it difficult if not impossible for composting operations to make use of it. The Australian and IPCC methodologies for determining GHG emissions of various manure management systems are based: (i) for nitrous oxide emissions, on the amount of nitrogen excreted (kg N_2O-N/kg N excreted) by animals, which in turn is based on the animals' crude protein input and storage and the subsequent output of nitrogen in faeces and urine; and (ii) for methane emissions, on the volatile solids component of the manure, which in turn is based on the animals' dry matter intake and digestibility and various other factors (Department of the Environment 2015b). While this approach might be suitable for estimating GHG emissions from various manure management systems that currently represent manure management options within the Australian National Greenhouse Accounts, the above methods of estimating emissions are difficult to maintain for composting because manures are frequently blended with other raw materials to enhance the composting process, reduce odour, and/or reduce nutrient losses. Blending of feedstocks for composting negates use of a methodology for estimating GHG emissions that is solely based on unutilised nutrient and volatile solids in animal feed. The marked variation in emissions per tonne manure seen in Table 6, particularly for methane and ammonia, demonstrate this point. Total emission per tonne wet manure for Windrows B and C, which were amended with increasing quantities of sawdust, were 66% and 390% higher, respectively, than those from Windrow A.

Composting is also a recognised biological treatment option for municipal and commercial waste materials, but the employed methodology is very different and much simpler (Department of the Environment 2014). In 2013, Australia adopted country-specific emission factors for 'waste composting' that were considerably lower than previously used IPCC emission factors (Table 14). However, the Department of the Environment subsequently adjusted the country-specific emission factors for composting slightly in 2015 and 2016 (Department of the Environment 2015a, 2016). The ten-fold reduction of the emission factor for nitrous oxide published in July 2017 (Department of the Environment 2017a), however, is inconsistent with the Technical Guidelines for the estimation of emissions by facilities in Australia, published in October 2017 (Department of the Environment 2017b), where the previous emission factor of 29 kg CO_2-e per tonne wet feedstock for nitrous oxide emissions from composting was still used. Already in 2015, the National Inventory Report 2013 (Department of the Environment 2015b) changed the nitrous oxide emission factor for the composting of waste from 30 to 2 kg CO_2-e per tonne wet feedstock. Yet the report retained the original sources of information and justification for adapting the country-specific emission factors for methane and nitrous oxide, and it also maintained National GHG emission levels due to biological waste treatment, except for the annual growth in material composted. Therefore, it is deemed very likely that the nitrous oxide emission factor of 2 kg CO_2-e per tonne wet feedstock for 'waste composting' is a typographical error.

Comparison of emission factors obtained for stockpiling and composting of chicken manure with the 2016 Australian default values for 'waste composting' shows that all recorded emissions are well below the default threshold values, even if indirect emissions caused by ammonia volatilisation are accounted for.

Table 14 Default emission factors for 'waste composting'

	GHG Emissions (kg per t wet feedstock as CO_2-e)		
	CH_4	N_2O	Total
IPCC	84	93	177
Australia (2013)	16	30	46
Australia (2015)	19	30	49
Australia (2016)	19	29	48
Australia (2017)	19	2	21

Consequently, the earlier call to align GHG emissions from secondary manure management systems such as stockpiling, composting, digestion or biocharring with those defined as 'biological waste treatment', and express them as emissions per tonne wet feedstock (Biala et al. 2016) is repeated and re-emphasised here. To enable comparison of emissions from primary and secondary manure management systems, and also allow for the addition of emissions from two different systems, emission factors from primary systems should be expressed also as emissions per tonne wet feedstock. The establishment of relatively simple and 'user-friendly' emission factors for composting and other secondary manure management systems is also desirable when it comes to the establishment and subsequent use of a methodology for the Emission Reduction Fund or subsequent funding mechanisms.

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6 Appendix

Windrow dimensions and calculation of emission surface areas for three windrows during the four-month composting trial.

Note: the dates displayed and periods stated refer to the days when windrows were turned and the periods between dates when the windrows were turned, respectively.

Windrow A													
Friday, 26 May 2017	**For period 19 May to 26 May**												
Row Length (m)	top	25.8											
	bottom	30.3											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9			Sum (m2)	Percentage
Widt - top (cm)	240.00	240.00	255.00	260.00	250.00	260.00	230.00	200.00	185.00				
Top surface area (m2)	6.88	6.88	7.31	7.45	7.17	7.45	6.59	5.73	5.30			60.77	100.0
Length	1.60	5.80	7.40	12.70	14.30	17.70	21.60	23.00	24.50				
Top surface area detailed (m2)	1.92	10.08	3.96	13.65	4.08	8.67	9.56	3.01	2.89	1.20		59.01	
Midpoint ammonia measurements				10.85		18.65							
Top surface area - ammonia (m2)	1.92	10.08	3.96	8.88	8.80	11.09	7.23	3.01	2.89	1.20		59.06	100.0
Top surface area - ammonia (m2)			24.84		19.89			14.33					
Monday, 5 June 2017	**For period 27 May to 5 June**												
Row Length (m)	top	28											
	bottom	32											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9				
Widt - top (cm)	220.00	245.00	250.00	290.00	280.00	260.00	200.00	190.00	180.00				
Top surface area (m2)	6.84	7.62	7.78	9.02	8.71	8.09	6.22	5.91	5.60			65.80	108.3
Length	2.40	5.90	8.00	12.40	14.60	17.50	21.00	23.30	25.80				
Top surface area detailed (m2)	2.64	8.14	5.20	11.88	6.27	7.83	8.05	4.49	4.63	1.98		61.10	
Midpoint ammonia measurements				11.30		18.95							
Top surface area - ammonia (m2)	2.64	8.14	5.20	8.91	9.41	11.75	4.72	4.49	4.63	1.98		61.84	104.7
Top surface area - ammonia (m2)			24.89		21.15			15.81					
Monday, 12 June 2017	**For period 6 June to 12 June**												
Row Length (m)	top	27.2											
	bottom	31											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	180.00	205.00	210.00	230.00	245.00	220.00	225.00	205.00	200.00	190.00			
Top surface area (m2)	4.90	5.58	5.71	6.26	6.66	5.98	6.12	5.58	5.44	5.17		57.39	94.4
Length	2.50	6.50	9.10	12.10	14.30	16.70	19.70	22.40	24.00	25.60			
Top surface area detailed (m2)	2.25	7.70	5.40	6.60	5.23	5.58	6.68	5.81	3.24	3.12	1.52	53.11	
Midpoint ammonia measurements				12.90			20.35						
Top surface area - ammonia (m2)	2.25	7.70	5.40	8.36	3.33	5.58	8.12	4.41	3.24	3.12	1.52	53.02	89.8
Top surface area - ammonia (m2)			23.71			17.03			12.29				
Thursday, 22 June 2017	**For period 13 June to 22 June**												
Row Length (m)	top	27.6											
	bottom	31.5											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	190.00	230.00	230.00	230.00	240.00	240.00	220.00	210.00	200.00	180.00			
Top surface area (m2)	5.24	6.35	6.35	6.35	6.62	6.62	6.07	5.80	5.52	4.97		59.89	98.5
Length	2.50	6.20	8.00	10.90	13.80	16.10	18.70	20.80	22.80	25.60			
Top surface area detailed (m2)	2.38	7.77	4.14	6.67	6.82	5.52	5.98	4.52	4.10	5.32	1.80	55.01	
Midpoint ammonia measurements				12.05			19.45						
Top surface area - ammonia (m2)	2.38	7.77	4.14	9.32	4.11	5.52	7.71	2.90	4.10	5.32	1.80	55.06	93.2
Top surface area - ammonia (m2)			23.60			17.34			14.12				
Monday, 3 July 2017	**For period 23 June to 3 July**												
Row Length (m)	top	27.2											
	bottom	31.3											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	200.00	200.00	220.00	230.00	220.00	220.00	210.00	200.00	190.00	190.00			
Top surface area (m2)	5.44	5.44	5.98	6.26	5.98	5.98	5.71	5.44	5.17	5.17		56.58	93.1
Length	3.30	6.70	9.00	12.70	16.10	18.10	19.90	22.10	24.10	25.60			
Top surface area detailed (m2)	3.30	6.80	4.83	8.33	7.65	4.40	3.87	4.51	3.90	2.85	1.52	51.96	
Midpoint ammonia measurements				13.55			21.10						
Top surface area - ammonia (m2)	3.30	6.80	4.83	10.24	5.74	4.40	6.45	2.05	3.90	2.85	1.52	52.08	88.2
Top surface area - ammonia (m2)			25.17			16.59			10.32				
Tuesday, 18 July 2017	**For period 4 July to 18 July (not measured, used data recorded on 3 July)**												
Row Length (m)	top	27.2											
	bottom	31.3											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	200.00	200.00	220.00	230.00	220.00	220.00	210.00	200.00	190.00	190.00			
Top surface area (m2)	5.44	5.44	5.98	6.26	5.98	5.98	5.71	5.44	5.17	5.17		56.58	93.1
Length	3.30	6.70	9.00	12.70	16.10	18.10	19.90	22.10	24.10	25.60			
Top surface area detailed (m2)	3.30	6.80	4.83	8.33	7.65	4.40	3.87	4.51	3.90	2.85	1.52	51.96	
Midpoint ammonia measurements				13.55			21.10						
Top surface area - ammonia (m2)	3.30	6.80	4.83	10.24	5.74	4.40	6.45	2.05	3.90	2.85	1.52	52.08	88.2
Top surface area - ammonia (m2)			25.17			16.59			10.32				
Tuesday, 1 August 2017	**For period 19 July to 31 July (not measured, used data recorded on 3 July)**												
Row Length (m)	top	27.2											
	bottom	31.3											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	200.00	200.00	220.00	230.00	220.00	220.00	210.00	200.00	190.00	190.00			
Top surface area (m2)	5.44	5.44	5.98	6.26	5.98	5.98	5.71	5.44	5.17	5.17		56.58	93.1
Length	3.30	6.70	9.00	12.70	16.10	18.10	19.90	22.10	24.10	25.60			
Top surface area detailed (m2)	3.30	6.80	4.83	8.33	7.65	4.40	3.87	4.51	3.90	2.85	1.52	51.96	
Midpoint ammonia measurements				13.55			21.10						
Top surface area - ammonia (m2)	3.30	6.80	4.83	10.24	5.74	4.40	6.45	2.05	3.90	2.85	1.52	52.08	88.2
Top surface area - ammonia (m2)			25.17			16.59			10.32				
Monday, 21 August 2017	**For period 1 Aug to 21 Aug**												
Row Length (m)	top	30.7											
	bottom	34.7											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11		
Widt - top (cm)	110.00	130.00	150.00	160.00	170.00	170.00	160.00	150.00	150.00	120.00	80.00		
Top surface area (m2)	3.07	3.63	4.19	4.47	4.74	4.74	4.47	4.19	4.19	3.35	2.23		43.26
Length	1.90	5.90	8.30	10.20	14.30	17.40	19.40	22.70	24.80	26.70	29.00		
Top surface area detailed (m2)	1.05	4.80	3.36	2.95	6.77	5.27	3.30	5.12	3.15	2.57	2.30	0.68	41.30
Midpoint ammonia measurements					14.80			23.05					
Top surface area - ammonia (m2)	1.05	4.80	3.36	2.95	7.59	4.42	3.30	5.66	2.63	2.57	2.30	0.68	41.29
Top surface area - ammonia (m2)				16.38			13.38			8.17			
Thursday, 31 August 2017	**For period 22 Aug to 31 Aug**												
Row Length (m)	top	23.3											
	bottom	27.3											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	130.00	140.00	170.00	165.00	170.00	160.00	140.00	130.00	140.00	110.00			
Top surface area (m2)	3.03	3.26	3.96	3.84	3.96	3.73	3.26	3.03	3.26	2.56		33.90	55.8
Length	2.40	4.90	6.50	8.70	10.10	12.10	14.40	17.60	19.20	20.80			
Top surface area detailed (m2)	1.56	3.38	2.48	3.69	2.35	3.30	3.45	4.32	2.16	2.00	1.38	30.05	
Midpoint ammonia measurements				9.30			15.65						
Top surface area - ammonia (m2)	1.56	3.38	2.48	4.69	1.34	3.30	5.33	2.63	2.16	2.00	1.38	30.24	51.2
Top surface area - ammonia (m2)			12.11			9.97			8.17				
Thursday, 7 September 2017	**For period 1 Sept to 22 Sept**												
Row Length (m)	top	25.2											
	bottom	29.7											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	100.00	115.00	135.00	140.00	140.00	120.00	120.00	110.00	100.00	90.00			
Top surface area (m2)	2.52	2.90	3.40	3.53	3.53	3.02	3.02	2.77	2.52	2.27		29.48	48.5
Length	3.50	6.20	8.10	11.10	13.70	15.80	18.40	20.90	22.90	24.20			
Top surface area detailed (m2)	1.75	2.90	2.38	4.13	3.64	2.73	3.12	2.88	2.10	1.24	0.45	27.30	
Midpoint ammonia measurements				11.95			19.35						
Top surface area - ammonia (m2)	1.75	2.90	2.38	5.29	2.45	2.73	4.26	1.78	2.10	1.24	0.45	27.33	46.3
Top surface area - ammonia (m2)			12.32			9.44			5.57				

Windrow B													
Friday, 26 May 2017	**For period 19 May to 26J May**												
Row Length (m)	top	22.2											
	bottom	26.2											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9			Sum (m2)	Percentage
Widt - top (cm)	265.00	260.00	240.00	265.00	260.00	260.00	255.00	240.00	200.00				
Top surface area (m2)	6.54	6.41	5.92	6.54	6.41	6.41	6.29	5.92	4.93			55.38	100.0
Length	1.80	4.80	6.20	10.00	11.60	14.00	16.70	18.00	19.90				
Top surface area detailed (m2)	2.39	7.88	3.50	9.60	4.20	6.24	6.95	3.22	4.18	2.30		50.45	
Midpoint ammonia measurements				8.90		14.80							
Top surface area - ammonia (m2)	2.39	7.88	3.50	6.82	7.09	8.32	4.89	3.22	4.18	2.30		50.58	100.0
Top surface area - ammonia (m2)			20.58		15.41			14.59					
Monday, 5 June 2017	**For period 27 May to 5 June**												
Row Length (m)	top	25											
	bottom	28.7											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9				
Widt - top (cm)	270.00	275.00	260.00	260.00	260.00	250.00	225.00	190.00	140.00				
Top surface area (m2)	7.50	7.64	7.22	7.22	7.22	6.94	6.25	5.28	3.89			59.17	106.8
Length	2.80	4.90	7.30	10.60	13.00	15.40	18.30	20.20	22.30				
Top surface area detailed (m2)	3.78	5.72	6.42	8.58	6.24	6.12	6.89	3.94	3.47	1.89		53.05	
Midpoint ammonia measurements				10.15		16.60							
Top surface area - ammonia (m2)	3.78	5.72	6.42	7.41	7.41	9.18	4.04	3.94	3.47	1.89		53.26	105.3
Top surface area - ammonia (m2)			23.33		16.59			13.34					
Monday, 12 June 2017	**For period 6 June to 12 June**												
Row Length (m)	top	25											
	bottom	28.5											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	220.00	260.00	255.00	260.00	260.00	260.00	260.00	250.00	230.00	215.00			
Top surface area (m2)	5.50	6.50	6.38	6.50	6.50	6.50	6.50	6.25	5.75	5.38		61.75	111.5
Length	2.90	5.60	7.90	10.70	12.50	14.60	16.50	18.40	20.60	22.80			
Top surface area detailed (m2)	3.19	6.48	5.92	7.21	4.68	5.46	4.94	4.85	5.28	4.90	2.37	55.27	
Midpoint ammonia measurements				11.25			17.60						
Top surface area - ammonia (m2)	3.19	6.48	5.92	8.63	3.25	5.46	7.80	2.04	5.28	4.90	2.37	55.31	109.4
Top surface area - ammonia (m2)			24.22			16.51			14.58				
Thursday, 22 June 2017	**For period 13 June to 22 June**												
Row Length (m)	top	25											
	bottom	29.3											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	210.00	260.00	280.00	260.00	255.00	240.00	240.00	210.00	180.00	120.00			
Top surface area (m2)	5.25	6.50	7.00	6.50	6.38	6.00	6.00	5.25	4.50	3.00		56.38	101.8
Length	2.20	4.40	6.50	10.00	12.70	14.90	17.00	18.50	20.50	23.00			
Top surface area detailed (m2)	2.31	5.17	5.67	9.45	6.95	5.45	5.04	3.38	3.90	3.75	1.20	52.26	
Midpoint ammonia measurements				10.70			17.70						
Top surface area - ammonia (m2)	2.31	5.17	5.67	11.34	5.15	5.45	6.72	1.80	3.90	3.75	1.20	52.46	103.7
Top surface area - ammonia (m2)			24.49			17.32			10.65				
Monday, 3 July 2017	**For period 23 June to 3 July**												
Row Length (m)	top	25.4											
	bottom	29.2											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	210.00	235.00	230.00	235.00	230.00	220.00	230.00	200.00	190.00	150.00			
Top surface area (m2)	5.33	5.97	5.84	5.97	5.84	5.59	5.84	5.08	4.83	3.81		54.10	97.7
Length	3.70	6.10	8.20	11.20	14.10	16.10	17.60	19.50	21.60	23.50			
Top surface area detailed (m2)	3.89	5.34	4.88	6.98	6.74	4.50	3.38	4.09	4.10	3.23	1.43	48.54	
Midpoint ammonia measurements				12.15			18.85						
Top surface area - ammonia (m2)	3.89	5.34	4.88	9.18	4.53	4.50	6.19	1.40	4.10	3.23	1.43	48.66	96.2
Top surface area - ammonia (m2)			23.29			15.22			10.15				
Tuesday, 18 July 2017	**For period 4 July to 18 July (not measured, used data recorded on 3 July)**												
Row Length (m)	top	25.4											
	bottom	29.2											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	210.00	235.00	230.00	235.00	230.00	220.00	230.00	200.00	190.00	150.00			
Top surface area (m2)	5.33	5.97	5.84	5.97	5.84	5.59	5.84	5.08	4.83	3.81		54.10	97.7
Length	3.70	6.10	8.20	11.20	14.10	16.10	17.60	19.50	21.60	23.50			
Top surface area detailed (m2)	3.89	5.34	4.88	6.98	6.74	4.50	3.38	4.09	4.10	3.23	1.43	48.54	
Midpoint ammonia measurements				12.15			18.85						
Top surface area - ammonia (m2)	3.89	5.34	4.88	9.18	4.53	4.50	6.19	1.40	4.10	3.23	1.43	48.66	96.2
Top surface area - ammonia (m2)			23.29			15.22			10.15				
Tuesday, 1 August 2017	**For period 19 July to 31 July (not measured, used data recorded on 3 July)**												
Row Length (m)	top	25.4											
	bottom	29.2											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	210.00	235.00	230.00	235.00	230.00	220.00	230.00	200.00	190.00	150.00			
Top surface area (m2)	5.33	5.97	5.84	5.97	5.84	5.59	5.84	5.08	4.83	3.81		54.10	97.7
Length	3.70	6.10	8.20	11.20	14.10	16.10	17.60	19.50	21.60	23.50			
Top surface area detailed (m2)	3.89	5.34	4.88	6.98	6.74	4.50	3.38	4.09	4.10	3.23	1.43	48.54	
Midpoint ammonia measurements				12.15			18.85						
Top surface area - ammonia (m2)	3.89	5.34	4.88	9.18	4.53	4.50	6.19	1.40	4.10	3.23	1.43	48.66	96.2
Top surface area - ammonia (m2)			23.29			15.22			10.15				
Monday, 21 August 2017	**For period 1 Aug to 21 Aug**												
Row Length (m)	top	28											
	bottom	30.8											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	150.00	155.00	180.00	190.00	180.00	170.00	165.00	160.00	135.00	110.00			
Top surface area (m2)	4.20	4.34	5.04	5.32	5.04	4.76	4.62	4.48	3.78	3.08		44.66	80.6
Length	3.10	5.70	7.70	11.30	14.20	16.00	19.20	22.30	24.20	26.70			
Top surface area detailed (m2)	2.33	3.97	3.35	6.66	5.37	3.15	5.36	5.04	2.80	3.06	0.72	41.79	
Midpoint ammonia measurements				11.85			20.10						
Top surface area - ammonia (m2)	2.33	3.97	3.35	7.68	4.35	3.15	6.87	3.58	2.80	3.06	0.72	41.84	82.7
Top surface area - ammonia (m2)			17.32			14.37			10.16				
Thursday, 31 August 2017	**For period 22 Aug to 31 Aug**												
Row Length (m)	top	28.7											
	bottom	31.9											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	125.00	140.00	140.00	160.00	155.00	140.00	130.00	140.00	130.00	115.00			
Top surface area (m2)	3.59	4.02	4.02	4.59	4.45	4.02	3.73	4.02	3.73	3.30		39.46	71.3
Length	3.90	6.20	8.10	11.30	14.90	17.00	20.20	22.20	24.20	26.10			
Top surface area detailed (m2)	2.44	3.05	2.66	4.80	5.67	3.10	4.32	2.70	2.70	2.33	1.50	35.26	
Midpoint ammonia measurements				12.55			20.60						
Top surface area - ammonia (m2)	2.44	3.05	2.66	6.68	3.70	3.10	4.86	2.16	2.70	2.33	1.50	35.16	69.5
Top surface area - ammonia (m2)			14.82			11.66			8.68				
Thursday, 7 September 2017	**For period 1 Sept to 22 Sept**												
Row Length (m)	top	27.8											
	bottom	31.6											
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10			
Widt - top (cm)	100.00	110.00	120.00	130.00	150.00	140.00	130.00	115.00	105.00	110.00			
Top surface area (m2)	2.78	3.06	3.34	3.61	4.17	3.89	3.61	3.20	2.92	3.06		33.64	60.7
Length	2.40	5.20	7.30	10.60	13.50	15.60	18.30	21.40	23.40	25.20			
Top surface area detailed (m2)	1.20	2.94	2.42	4.13	4.06	3.05	3.65	3.80	2.20	1.94	1.43	30.79	
Midpoint ammonia measurements				11.45			19.50						
Top surface area - ammonia (m2)	1.20	2.94	2.42	5.19	2.87	3.05	5.27	2.33	2.20	1.94	1.43	30.82	60.9
Top surface area - ammonia (m2)			11.74			11.18			7.89				

Windrow C														
Friday, 26 May 2017	**For period 19 May to 26J May**													
Row Length (m)	top	21.8												
	bottom	25.6												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8				Sum (m2)	Percentage	
Widt - top (cm)	280.00	280.00	280.00	285.00	270.00	275.00	265.00	185.00						
Top surface area (m2)	7.63	7.63	7.63	7.77	7.36	7.49	7.22	5.04				57.77	100.0	
Length	1.60	3.90	5.80	9.00	11.10	13.70	16.00	19.40						
Top surface area detailed (m2)	2.24	6.44	5.32	9.04	5.83	7.09	6.21	7.65	2.22			52.03		
Midpoint ammonia measurements				8.45		13.55								
Top surface area - ammonia (m2)	2.24	6.44	5.32	7.49	7.35	6.68	6.62	7.65	2.22			52.00	100.0	
Top surface area - ammonia (m2)			21.49		14.03		16.49							
Monday, 5 June 2017	**For period 27 May to 5 June**													
Row Length (m)	top	24.4												
	bottom	28.4												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9					
Widt - top (cm)	290.00	310.00	315.00	310.00	310.00	310.00	250.00	220.00	150.00					
Top surface area (m2)	7.86	8.40	8.54	8.40	8.40	8.40	6.78	5.96	4.07			66.83	115.7	
Length	2.50	4.50	6.60	9.30	11.40	14.10	16.70	19.10	21.30					
Top surface area detailed (m2)	3.63	6.00	6.56	8.44	6.51	8.37	7.28	5.64	4.07	2.33		58.82		
Midpoint ammonia measurements				9.00		14.05								
Top surface area - ammonia (m2)	3.63	6.00	6.56	7.50	7.44	8.22	7.42	5.64	4.07	2.33		58.80	113.1	
Top surface area - ammonia (m2)			23.69		15.66		19.46							
Monday, 12 June 2017	**For period 6 June to 12 June**													
Row Length (m)	top	25.2												
	bottom	28.8												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10				
Widt - top (cm)	250.00	270.00	280.00	295.00	300.00	290.00	280.00	260.00	230.00	170.00				
Top surface area (m2)	6.30	6.80	7.06	7.43	7.56	7.31	7.06	6.55	5.80	4.28		66.15	114.5	
Length	3.40	5.80	8.60	9.60	11.10	13.40	16.10	18.40	20.60	23.50				
Top surface area detailed (m2)	4.25	6.24	7.70	2.88	4.46	6.79	7.70	6.21	5.39	5.80	1.45	58.85		
Midpoint ammonia measurements				11.00			17.00							
Top surface area - ammonia (m2)	4.25	6.24	7.70	6.90	0.30	6.79	10.26	3.78	5.39	5.80	1.45	58.85	113.2	
Top surface area - ammonia (m2)			25.09			17.34			16.42					
Thursday, 22 June 2017	**For period 13 June to 22 June**													
Row Length (m)	top	26												
	bottom	30.1												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10				
Widt - top (cm)	255.00	295.00	300.00	305.00	285.00	280.00	255.00	230.00	195.00	160.00				
Top surface area (m2)	6.63	7.67	7.80	7.93	7.41	7.28	6.63	5.98	5.07	4.16		66.56	115.2	
Length	2.50	5.30	7.60	9.90	12.70	14.90	16.60	18.50	20.70	23.30				
Top surface area detailed (m2)	3.19	7.70	6.84	6.96	8.26	6.22	4.55	4.61	4.68	4.62	2.16	59.77		
Midpoint ammonia measurements				11.25			17.80							
Top surface area - ammonia (m2)	3.19	7.70	6.84	11.04	4.28	6.22	7.76	1.70	4.68	4.62	2.16	60.17	115.7	
Top surface area - ammonia (m2)			28.77			18.25			13.15					
Monday, 3 July 2017	**For period 23 June to 3 July**													
Row Length (m)	top	25.4												
	bottom	29.4												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10				
Widt - top (cm)	180.00	245.00	260.00	265.00	270.00	255.00	230.00	225.00	200.00	160.00				
Top surface area (m2)	4.57	6.22	6.60	6.73	6.86	6.48	5.84	5.72	5.08	4.06		58.17	100.7	
Length	2.70	5.50	7.40	10.20	13.50	15.40	17.10	18.80	20.90	22.80				
Top surface area detailed (m2)	2.43	5.95	4.80	7.35	8.83	4.99	4.12	3.87	4.46	3.42	2.08	52.30		
Midpoint ammonia measurements				11.40			18.15							
Top surface area - ammonia (m2)	2.43	5.95	4.80	10.50	5.62	4.99	6.67	1.48	4.46	3.42	2.08	52.39	100.8	
Top surface area - ammonia (m2)			23.68			17.27			11.44					
Tuesday, 18 July 2017	**For period 4 July to 18 July (not measured, used data recorded on 3 July)**													
Row Length (m)	top	25.4												
	bottom	29.4												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10				
Widt - top (cm)	180.00	245.00	260.00	265.00	270.00	255.00	230.00	225.00	200.00	160.00				
Top surface area (m2)	4.57	6.22	6.60	6.73	6.86	6.48	5.84	5.72	5.08	4.06		58.17	100.7	
Length	2.70	5.50	7.40	10.20	13.50	15.40	17.10	18.80	20.90	22.80				
Top surface area detailed (m2)	2.43	5.95	4.80	7.35	8.83	4.99	4.12	3.87	4.46	3.42	2.08	52.30		
Midpoint ammonia measurements				11.40			18.15							
Top surface area - ammonia (m2)	2.43	5.95	4.80	10.50	5.62	4.99	6.67	1.48	4.46	3.42	2.08	52.39	100.8	
Top surface area - ammonia (m2)			23.68			17.27			11.44					
Tuesday, 1 August 2017	**For period 4 July to 18 July (not measured, used data recorded on 3 July)**													
Row Length (m)	top	25.4												
	bottom	29.4												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10				
Widt - top (cm)	180.00	245.00	260.00	265.00	270.00	255.00	230.00	225.00	200.00	160.00				
Top surface area (m2)	4.57	6.22	6.60	6.73	6.86	6.48	5.84	5.72	5.08	4.06		58.17	100.7	
Length	2.70	5.50	7.40	10.20	13.50	15.40	17.10	18.80	20.90	22.80				
Top surface area detailed (m2)	2.43	5.95	4.80	7.35	8.83	4.99	4.12	3.87	4.46	3.42	2.08	52.30		
Midpoint ammonia measurements				11.40			18.15							
Top surface area - ammonia (m2)	2.43	5.95	4.80	10.50	5.62	4.99	6.67	1.48	4.46	3.42	2.08	52.39	100.8	
Top surface area - ammonia (m2)			23.68			17.27			11.44					
Monday, 21 August 2017	**For period 1 Aug to 21 Aug**													
Row Length (m)	top	29												
	bottom	32.5												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10				
Widt - top (cm)	145.00	190.00	230.00	225.00	230.00	220.00	215.00	170.00	150.00	120.00				
Top surface area (m2)	4.21	5.51	6.67	6.53	6.67	6.38	6.24	4.93	4.35	3.48		54.96	95.1	
Length	3.40	6.00	8.10	10.40	12.00	14.10	17.30	19.10	21.70	26.10				
Top surface area detailed (m2)	2.47	4.36	4.41	5.23	3.64	4.73	6.96	3.47	4.16	5.94	1.74	47.09		
Midpoint ammonia measurements				11.10			16.60							
Top surface area - ammonia (m2)	2.47	4.36	4.41	6.83	2.05	4.73	5.44	4.81	4.16	5.94	1.74	46.92	90.2	
Top surface area - ammonia (m2)			18.06			12.21			16.65					
Thursday, 31 August 2017	**For period 22 Aug to 31 Aug**													
Row Length (m)	top	28												
	bottom	32												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11			
Widt - top (cm)	150.00	170.00	175.00	180.00	190.00	190.00	185.00	170.00	150.00	130.00	110.00			
Top surface area (m2)	3.82	4.33	4.45	4.58	4.84	4.84	4.71	4.33	3.82	3.31	2.80		43.02	74.5
Length	2.50	4.50	6.70	9.20	11.30	13.20	15.30	17.20	19.20	22.10	25.20			
Top surface area detailed (m2)	1.88	3.20	3.80	4.44	3.89	3.61	3.94	3.37	3.20	4.06	3.72	1.54	40.63	
Midpoint ammonia measurements				9.95			16.20							
Top surface area - ammonia (m2)	1.88	3.20	3.80	5.77	2.50	3.61	5.63	1.78	3.20	4.06	3.72	1.54	40.67	78.2
Top surface area - ammonia (m2)			14.64			11.73			12.76					
Thursday, 7 September 2017	**For period 1 Sept to 22 Sept**													
Row Length (m)	top	30.2												
	bottom	33.4												
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11			
Widt - top (cm)	110.00	140.00	140.00	155.00	170.00	165.00	155.00	155.00	135.00	110.00	90.00			
Top surface area (m2)	3.02	3.84	3.84	4.26	4.67	4.53	4.26	4.26	3.71	3.02	2.47		41.87	72.5
Length	3.00	6.30	8.30	11.00	13.00	15.30	17.60	20.10	22.20	24.80	27.50			
Top surface area detailed (m2)	1.65	4.13	2.80	3.98	3.25	3.85	3.68	3.88	3.05	3.19	2.70	1.22	37.36	
Midpoint ammonia measurements				11.80			18.75							
Top surface area - ammonia (m2)	1.65	4.13	2.80	5.16	1.95	3.85	5.52	2.09	3.05	3.19	2.70	1.22	37.30	71.7
Top surface area - ammonia (m2)			13.74			11.32			12.24					