


Revised methane emission factors and parameters for dairy effluent ponds

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Landcare Research
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Summary

The current New Zealand Greenhouse Gas Inventory estimated that, in 2010, dairy effluent management accounted for 420 Gg CO_2-e of methane (CH_4) emissions. Approximately 340 Gg CO_2-e (80%) of these emissions came from anaerobic dairy effluent ponds (the remaining 20% was from manure deposited on pastures). However, the current Inventory equation used to calculate CH_4 emissions from dairy effluent ponds relies on a bubble-counting method for measuring CH_4 emissions in one field study to estimate CH_4 fluxes. The bubble-counting method was prone to human error (e.g., some bubbles may have been visually overlooked and the sizes of the bubbles may not have been consistent) and did not take into account CH_4 diffusion from the pond. Moreover, the equation uses average pond dimensions, rather than digestible carbon loading rates, to scale-up CH_4 emissions from ponds across New Zealand. A recent study measuring CH_4 fluxes from a dairy effluent pond using a gas collection system and flow meter documented a CH_4 emission rate double (per cow) that reported in the current Inventory, suggesting CH_4 emission rates from ponds may be much higher than reported. Countering this, the Inventory currently assumes that all New Zealand dairy farms have an anaerobic pond. Although the number of dairy farms using ponds is increasing, in some regions milking shed effluent is discharged directly to pasture from a sump which would generate negligible CH_4 emissions. However, until this study, there has been no information on dairy effluent pond usage across New Zealand. Clearly, there is a need to establish a more rigorous estimate of CH_4 emissions from dairy effluent ponds, not just for national GHG accounting, but also to develop effective mitigation strategies.

Our research aim was to provide a more accurate estimate of CH_4 emissions from dairy effluent ponds than is currently reported in the national GHG Inventory. There were three key objectives.

> Objective 1 – Develop a robust CH_4 conversion factor for dairy effluent entering anaerobic ponds.
>
> Objective 2 – Measure CH_4 emissions from several dairy farm effluent ponds across different climatic regions.
>
> Objective 3 – Quantify the major effluent management practices on NZ dairy farms with a particular focus on the number of farms that have some form of anaerobic pond (either 2–3–4 pond treatment systems or single storage ponds).

The information obtained from each of the 3 objectives was combined to estimate CH_4 emissions from dairy effluent ponds across New Zealand. An experimental CH_4 yield of 489 Gg CO_2-e from dairy ponds for 2010 was calculated using a) the CH_4 conversion rate for dairy manure solids derived in Objective 1 and b) scaling-up to the proportional usage (i.e. 73.5%) of effluent ponds on dairy farms across New Zealand (determined in Objective 3). A sensitivity analysis showed that the experimental CH_4 yield from dairy effluent ponds ranged from 424 to 647 Gg CO_2-e in 2010, depending on variability in important variables such as volatile solids loading rates into ponds and CH_4 conversion factors. These lower and upper values are 1.7 × and 2.6 × higher, respectively, than the corrected CH_4 emission yield reported from dairy effluent ponds in the Inventory in 2010 (note, the 2010 Inventory value was corrected because 100% use of dairy effluent ponds was assumed in that document rather than the 73.5% usage rate reported in this work).

Combining the field data from Objective 2 with effluent pond usage rates across New Zealand yielded a total CH_4 estimate of 972 Gg CO_2-e, which is almost 4 × higher than the corrected 2010 Inventory value (MfE, 2012). The difference between the experimental and field-based yields may relate to a number of factors outside the scope of this study. These include: 1) additional organic materials entering ponds, such as waste milk, and 2) a higher volume of manure entering ponds than currently reported. Both these factors were not accounted for in the experimental CH_4 calculation reported here, but were inherently factored-into the field-based calculation.

We conclude from our research that the New Zealand Greenhouse Gas Inventory is currently underestimating CH_4 emissions from dairy effluent ponds by a factor of at least 1.7 to 4, even considering the most conservative case in the sensitivity analysis. This factor is likely to be higher still as many farmers use feed pads and standoff pads. Furthermore, there is a move away from direct land irrigation of effluent towards systems that incorporate an effluent storage pond in more regions of NZ. This will mean that CH_4 emissions from ponds are likely to increase in the near future. Future research needs to address these changing farming practices to accurately account for CH_4 emissions from dairy effluent ponds and to develop suitable mitigation technologies.

1 Introduction

A Tier-2 approach, aligning with the International Panel on Climate Change guidance on good practice, is used in the New Zealand Greenhouse Gas (GHG) Inventory to estimate methane (CH_4) emissions from dairy effluent management (MfE, 2012). The approach is based upon an estimated partitioning between manure deposited on pastures and effluent stored in anaerobic lagoons or ponds. It also relies on estimates of the quantity of manure dry matter produced by dairy cattle and a CH_4 emission factor for manure deposited on pastures and another factor for manure stored in anaerobic ponds. Methane emissions from dairy effluent ponds account for the greatest GHG contribution from the manure management section in the national Inventory. Emissions from this source are calculated using the following equation (MfE, 2012):

Eqn 1 – $M = (FDM \times MMS) \times W/1000/d \times Ym$

Where, M = methane from manure management
MMS = proportion of faecal material deposited in lagoons/ponds
W = water dilution rate (litres per kg faecal dry matter)
d = average depth of a lagoon (metres)
Ym = methane yield (g CH_4 *per* m^2 *per year).*

Based on the most recently published calendar year in the current national GHG Inventory (2010) CH_4 emissions from anaerobic dairy effluent ponds were calculated as 340 Gg of CO_2-equivalents (MfE, 2012). The key figure used to determine this value is the *Ym* variable in Eqn 1 which is 3.27 kg m^{-2} y^{-1} (MfE, 2012). However, that flux rate was derived from a single study (McGrath & Mason, 2004) that employed an observational bubble-counting method to estimate emissions from a dairy effluent pond. Moreover, this flux rate is computed into a convoluted equation in the Inventory that calculates CH_4 emissions across all New Zealand dairy effluent ponds as a function of average pond dimensions. In practise it is the digestible carbon-loading rate into ponds, rather than the pond dimensions, that will determine the magnitude of CH_4 emissions.

Recently, a study by Craggs et al. (2008) documented a CH_4 emission rate double (on a per cow basis) that used in the current Inventory, for a commercial dairy effluent pond in the Waikato using a gas collection cover and flow meter. This result challenges the accuracy of the emission rate reported in the Inventory, and suggests that CH_4 emission rates from ponds may be much higher than currently reported. Tempering this is the assumption in the Inventory that all NZ dairy farms have an anaerobic effluent pond. This assumption is not well-founded as some farms discharge effluent directly to pasture year-round from a small sump; in these instances, the effluent would remain aerobic and CH_4 emissions would be low. However, there is very little information on the proportional usage of various effluent storage and treatment practices on NZ dairy farms.

Clearly, research is needed to more accurately quantify CH_4 emission rates from New Zealand dairy farm effluent ponds. A much better understanding of emission yields is needed on a nation-wide basis for Inventory reporting. Moreover, improved knowledge of CH_4 emission rates from dairy effluent ponds will help to guide the development of effective mitigation technologies to offset these emissions.

2 Objectives

The main aim of this research was to provide a more accurate estimate of CH_4 emissions from dairy effluent ponds than is currently reported in the national GHG Inventory. We had three objectives for this research:

> Objective 1 – Develop a robust CH_4 conversion factor for dairy effluent entering anaerobic ponds.
>
> Objective 2 – Measure CH_4 emissions from several dairy farm effluent ponds across different climatic regions.
>
> Objective 3 – Quantify the major effluent management practices on NZ dairy farms with a particular focus on the number of farms that have some form of anaerobic pond (either 2–4 pond treatment systems or single storage ponds).

Results from Objective 1 will be combined with data from Objective 3 to derive an experimental CH_4 yield from New Zealand's dairy effluent ponds as a function of manure loading rates. This yield will be verified by combining data from Objectives 2 and 3, which will provide a more accurate estimate of emissions from dairy farm effluent ponds in NZ based on field data. Overall, we envisaged that the results of this work would provide a more robust Inventory methodology than is used at present for estimating CH_4 emissions from New Zealand's dairy effluent ponds.

3 Materials and Methods

3.1 Determining methane conversion factors for dairy effluent in anaerobic ponds

The biochemical methane potential (BMP) of freshly voided dairy cattle manure was quantified monthly for a period of 12-months from June 2011 to May 2012. Fresh dairy-cattle manure was sourced from the Massey Dairy Research Farm no.4, Palmerston North, New Zealand. From December 2011, samples from NIWA's regional monitoring dairy farms were added to our monitoring program. These included:

- Northland (Waipu, 800 cows),
- Waikato (Hamilton, 700 cows)
- Southland (Gore, 920 cows).

Samples were collected randomly (minimum three dung patches) within the cattle holding-pad adjacent to the milking shed, stored in clean plastic containers, and returned/couriered to the laboratory immediately upon collection.

Characterisation for total and volatile solids (TS and VS) and volatile suspended solids (VSS) follows Standard Methods 2540E (samples were oven-dried at 105^{o}C to determine VS and then ashed to determine VS). Total and soluble chemical oxygen demand (tCOD and sCOD) were analyzed using the Standard Method closed reflux calorimetric method 5220D (samples are initially digested by a strong oxidising agent and then the organic content of the extracts are assessed based on the extant of colour change after reaction with a metal complex). pH and pressure (relative) was determined by hand-held pH meter (Global Science, model TPS WP-91) and pressure meters (Sper Scientific model 68601-00), respectively.

The BMP was quantified in serum flasks supplied with diluted manure (10% w/v) inoculated with an active acclimatized laboratory-grown inoculum fed with manure. The inoculum was added to reach a inoculum-to-substrate (ISR) ratio of 2 g/g and a substrate concentration of >3.5 gVS/L. All assays were prepared in duplicates and incubated in sealed glass serum bottles (118mL) maintained under anaerobic mesophilic conditions (35±2˚C), and monitored periodically for gas production (typically about every 30-45 days). In order to calculate the ultimate BMP value, biogas production was assumed to follow first-order kinetics (a good fit was experimentally verified). The concentrations of CH_4, carbon dioxide (CO_2) and hydrogen (H_2) in the biogas were determined by injecting gas samples into a Shimadzu gas chromatograph (GC-2014) equipped with thermal conductivity detector (external calibration).

3.2 Field measurements of methane fluxes from anaerobic dairy effluent ponds

Location and description of anaerobic ponds

The annual variation in production and composition of biogas from two New Zealand dairy farm anaerobic ponds (one in Northland, North Island and one in the Southland, South Island) were measured over one year. The Northland anaerobic pond (36.00.57S, 174.27.55E) was located on an 800 cow dairy farm near Waipu, 35 km South East of Wangarei. The farm provides year-round milk supply, with part of the herd calving at different times throughout the year. The number of cows milked per day varied between 800 from the beginning of September to mid-January and around 500 throughout the rest of the year. The herd was a Friesian dominated Jersey-Friesian cross (which is typical of New Zealand dairy farms) with an average live-weight of 450 kg/cow. During the 2011/2012 dairy season the Northland farm achieved a production of 323,000 kg milk solids (404 kg/cow/year) on a primarily pasture-grass diet.

The anaerobic pond was the first pond in a conventional 4-pond treatment system, with pasture irrigation as final effluent discharge. The pond was irregularly shaped, with a depth of ~2.5 m, a bund slope of approximately 1:1.5 (vertical:horizontal), and had mid-depth area of ~1000 m^2 and pond volume of ~2750 m^3. The farm did have a feedpad, although the feedpad effluent was treated separately.

The Southland anaerobic pond (46.06.04S, 169.06.48E) was located 5 km east of Gore and received effluent from the seasonal milking of ~920 pasture fed cows. This herd was a Friesian dominated Jersey-Friesian cross with an average live-weight of 490 kg/cow. During the 2011/2012 dairy season the Southland farm achieved a production of 430,000 kg milk solids (467 kg/cow/year), on a pasture-grass diet that was supplemented with barley, whole crop silage and molasses at strategic times of the year. Cow manure was washed from the milking shed yard and flowed by gravity through a grit trap and into a conventional anaerobic pond; this pond was the first of an Advanced Pond System (Craggs et al., 2003). The anaerobic pond was “U” shaped with a surface area of ~1600 m^2 (~43.5 m × ~42.5 m with a

24 m × 7 m central baffle). The pond was 4 m deep with a bund slope of approximately 1:1 (vertical:horizontal), giving a pond volume of ~4200 m^3 and a mid-depth area of ~1050 m^2.

Biogas production and composition data were also collected from two additional New Zealand dairy farm anaerobic ponds (one in the Waikato, North Island and one in Canterbury, South Island). The Waikato anaerobic pond was located 9 km SE of Hamilton (37.65S, 175.45E) and received milking shed wastewater from ~700 pasture fed cows. Cow manure was washed from the milking shed yard to a sump and pumped into a conventional anaerobic pond, the first pond of an Advanced Pond System (Craggs et al. 2003). The surface area of the anaerobic pond was ~1760 m^2 (43 m × 41 m). The pond was 4 m deep with a bund slope of approximately 1:2 (vertical:horizontal), giving a pond volume of ~4,600 m^3 and mid-depth area of 1,153 m^2 (Craggs et al., 2008). Data from the Waikato pond were recorded for a 9-month period only (April 2011 – December 2011) as modifications to the farm effluent system in January 2012 necessitated the removal of all recording equipment.

Due to problems with crust accumulation under the gas collection covers, reliable data were unable to be collected from the Canterbury farm.

Floating gas collection cover

A floating gas collection cover was positioned centrally on the surface of each of the anaerobic ponds. The covers (25 m^2) were constructed from polypropylene sheet welded to form a top surface with four sides, that was supported internally around the perimeter by a 5 m × 5 m floating frame (made from air-filled 100 mm diameter PVC stormwater pipe and fittings) and at the centre by a floating 200 L drum (Fig. 1). The four sides of the cover extended down from the support frame into the anaerobic pond to a depth of 0.5 m and were weighted using a metal chain within a sleeve along the bottom.

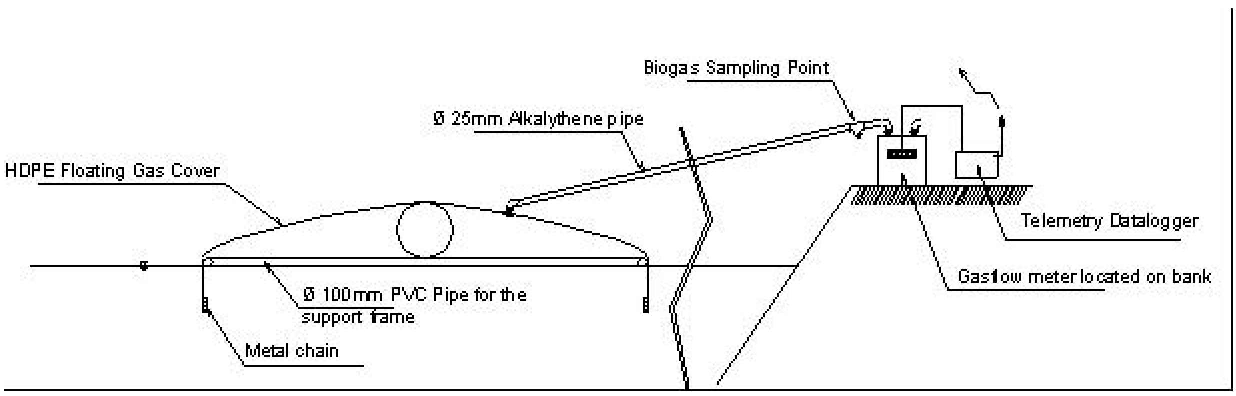

Figure 1 Schematic diagram of biogas collection, logging and data acquisition equipment.

Monitoring

Biogas flow was continually monitored using a domestic gas flow meter (Combustion Control (NZ) Ltd) on the pond bank which was connected to the biogas collection cover by a pipeline (25 mm diameter Polyethylene). This was attached to a 5-mm wire cable that sloped up from the biogas collection cover to the pond bank, enabling any condensed water to drain from the pipeline. A telemetry data acquisition system was installed to log biogas flow which consisted of a magnetic event sensor fitted within the biogas flow meter that generated a pulse output for every 1 litre of biogas flow (Fig. 1). Thermocouple sensors were installed to measure pond bottom (sludge), pond mid water depth and near surface water temperature as well as biogas temperature. Biogas flow and temperature data were logged continuously and transmitted at 15 minute intervals (Neon logger, Unidata Pty Ltd, Australia), and were downloaded daily through a cellphone modem. All biogas production data were corrected to standard temperature (15^{o}C), using the equation of Gay-Lussac. Ambient pressure data, obtained from the nearest weather station, e.g., Whangarei Aero Club for the Northland pond, indicated a discrepancy of only ~ 0.09% between annual average ambient air pressure and standard gas condition pressure of 1013 mbar. Biogas measurements were, therefore, not individually corrected for standard pressure conditions.

The composition of the biogas (CH_4, CO_2, O_2, and H_2S) was determined at monthly intervals using a portable gas analyser (GA2000plus Landfill Gas Analyser, Geotechnical Instruments (UK) Ltd, Leamington Spa, England). The gas analyser was calibrated biannually with certified standard gases and routinely checked against an artificial biogas. To determine the removal efficiency of the ponds' solids, total solids (TS), volatile solids (VS) and chemical oxygen demand (COD) of pond influent and effluent, grab samples were analysed at regular intervals. Some effluent samples were also analysed for volatile fatty acids, as an indicator of solids and biogas potential loss from the pond. All analysis was carried out according to standard methods (APHA, 1998).

3.3 Determining extent of anaerobic pond use across New Zealand dairy farms

This part of the work was conducted by synthesising data from previous reports and contacting staff from representative dairying and regulatory organisations. Figures on herd sizes were obtained from 'New Zealand Dairy Statistics 2010–2011' (DairyNZ, 2011), and corroborated by information from NZ govt. (2012), and regional and district council staff. The number of anaerobic dairy effluent ponds in each of New Zealand's 16 regions was determined through information given by regional council staff. For the Southland region, information on anaerobic pond use was provided by DairyNZ staff who noted that the installation of storage ponds on farms in this region will become widespread in the coming year.

Most councils were able to provide databases confirming the presence or absence of an effluent pond on each farm within their region. For the Canterbury region, which contains about 15% of New Zealand's dairy cows, the council could not provide information on the presence/absence of anaerobic ponds on farms. However, they did provide records of effluent storage times for every farm in the region. Personal communications from an Environment Canterbury (ECan) staff member indicated that farms with consents for greater than 1 week effluent storage would most likely make use of some form of storage or treatment pond. By contrast, for farms where storage was less than 1 week, a sump for direct irrigation was likely to be used instead. Based on this information, farms in the Canterbury region with consents for effluent storage greater than 1 week were considered to have an anaerobic effluent pond.

In most regions (with the exception of Waikato, Auckland, Gisborne, Tasman and Marlborough) council databases did not differentiate between 2-3-4 stage treatment ponds and single storage ponds. Hence, only the total number of anaerobic effluent ponds (i.e., the first pond in treatment systems or single storage ponds) in each region is reported in this study.

4 Results and Discussion

4.1 Methane conversion factors – dairy effluent

The results from the characterisation of raw fresh dairy cattle manure are shown in Table 1. As can be seen, there is a significant variation in the manure properties which may be explained by temporal variations in feed composition and metabolism. The VS/TS ratio was, however, more stable with an average value of 0.77 ± 0.02 g/g. Across the locations considered, the manure from Farm 4 was more concentrated in VS and TS than the other 3 farms, but not statistically different (ANOVA, $p = 0.05$) from the VSS and tCOD concentrations.

Table 1 Characterisation of raw dairy cattle manure from various dairy farms – monthly mean and standard deviation from June 2011 to March 2012

Parameter	Mean	s.d	C.I. (95%)	n
pH	7.05	0.13	0.04	40
Total solids, TS (g/L)	107.2	22.1	6.86	40
Volatile solids, VS (g/L)	81.9	15.0	4.65	40
Volatile suspended solids, VSS (g/l)	76.0	11.3	3.49	40
Total COD, tCOD (g/L)	170.9	33.8	10.47	40
Soluble COD, sCOD (g/L)	24.4	11.4	3.53	40

Under controlled laboratory conditions, the ultimate CH_4 potential (Bo) of dairy manure was found to be 0.22 ± 0.02 m^3 CH_4/kgVS added (Fig. 2). This result is in good agreement with the 0.24 m^3 CH_4/kgVS added reported by the IPCC and by numerous researchers (e.g. Labatut et al., 2011). Monthly Bo results showed variability (95% CI: 0.195 – 0.243) but no definite trend could be inferred on a seasonal basis.

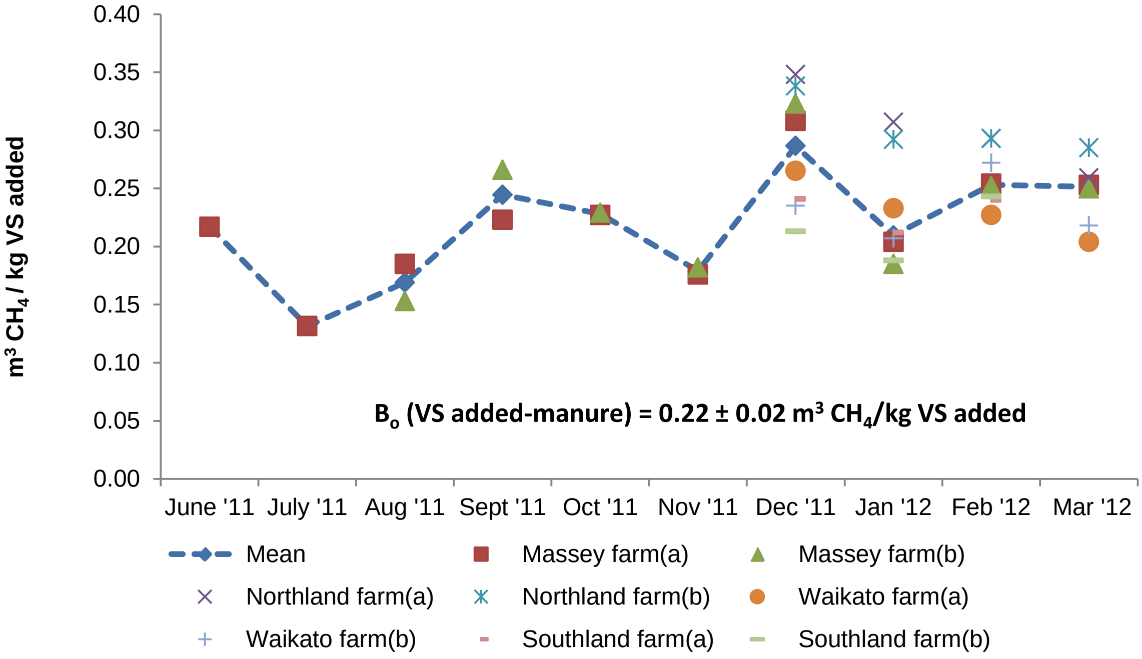

Figure 2 Monthly CH_4 potentials of fresh dairy cattle manure from various dairy farms ($m^3CH_4/kg/VS$ added). Labels a) and b) refer to different locations within the farm.

4.2 Methane fluxes from anaerobic dairy effluent ponds

The temperature data for the 12-month monitoring period (May 2011 – April 2012) for the Northland anaerobic pond is summarized in Figure 3. The near surface water temperature had a much greater variation than both the mid-water depth and sludge temperatures, but temperatures at all depths varied seasonally. The minimum winter temperatures in the anaerobic pond were typically greater than 12°C, while summer maximum temperatures were generally below 25°C, indicating stable temperature conditions for anaerobic digestion.

The temperature data for the 12-month monitoring period (May 2011 – April 2012) for the Southland anaerobic pond showed a very similar pattern (Fig. 4), but was on average 5°C lower than the temperatures recorded in Northland. During the winter, both the Northland and Southland ponds had warmer bottom sludge temperatures than surface temperatures. In particular, the winter Southland pond surface and mid-water depth temperatures declined to <3 °C, while the pond bottom temperature never declined below 6.5 °C, providing an anaerobic environment that was >3 °C warmer than the upper layers of the pond for over 2 months. Despite these low temperatures, and a lack of manure substrate entering the pond during the milking “dry season”, biogas production at the Southland site did not cease entirely.

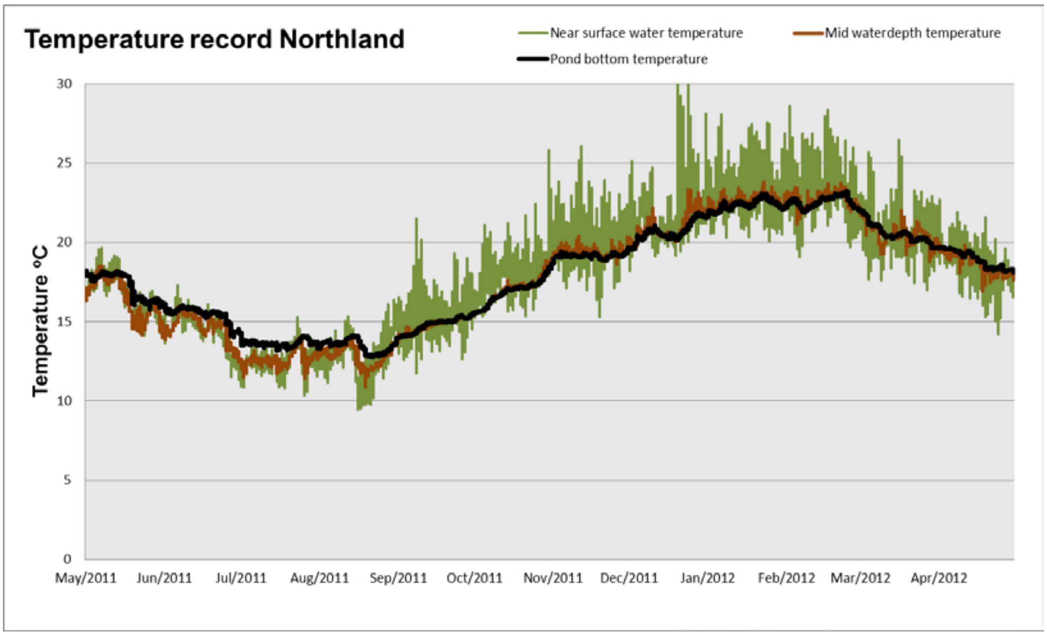

Figure 3 12 month temperature record from the Northland anaerobic pond.

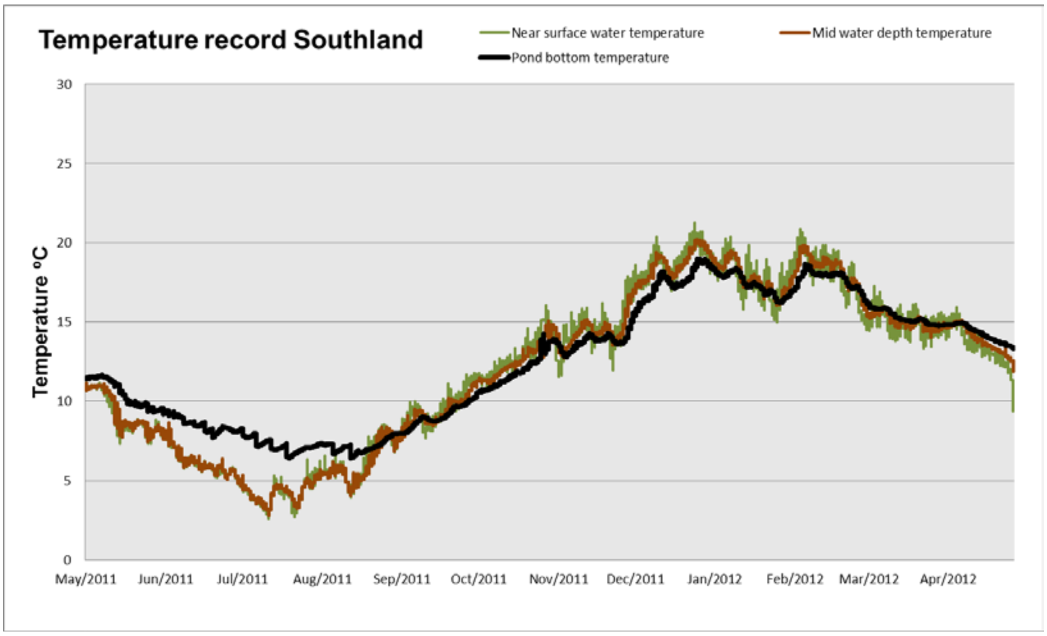

Figure 4 12 month temperature record from the Southland pond.

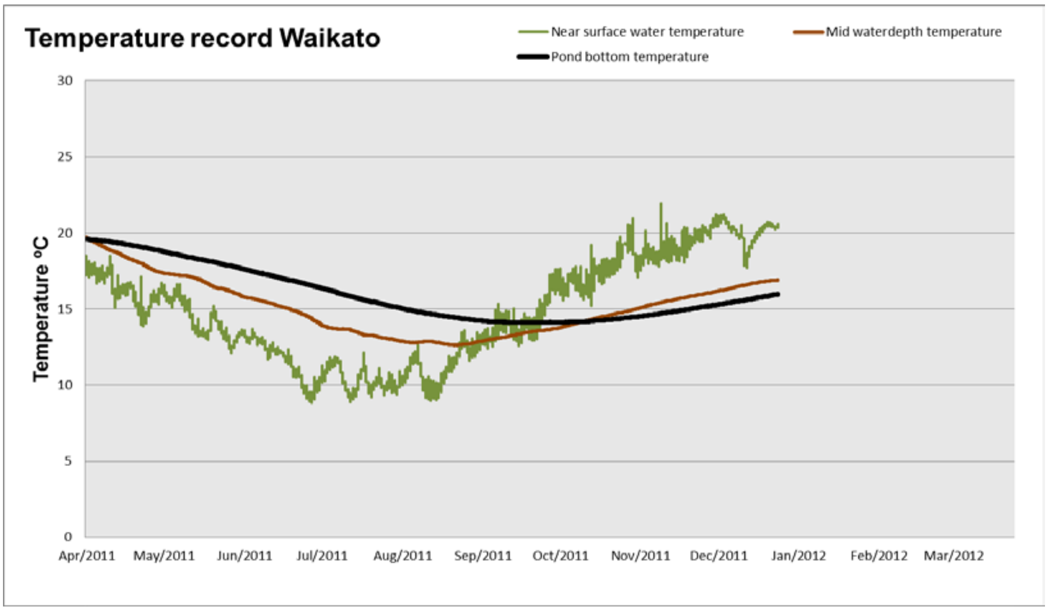

Figure 5 9 month temperature record from the Waikato pond.

The 9 month temperature record from the Waikato pond broadly follows the pattern observed in Northland with pond bottom, mid-depth and near surface water temperatures varying seasonally in a narrow band between ~ 10 and 20 ^{o}C (Fig. 5). Compared with Northland mid-depth and pond bottom, temperatures for the Waikato pond were much more stable. Moreover, pond bottom and mid-depth temperatures at Waikato were warmer than the near surface water temperature (similar to the Southland pond), which may be a reflection of the greater water depth of 4 m (compared to ~2.5m in Northland).

Table 2 Northland anaerobic pond solids and COD data

Sampling date	Influent TS g/m^3	Influent VS g/m^3	Influent COD g/m^3	Effluent TS g/m^3	Effluent VS g/m^3	Effluent COD g/m^3
2/06/2011				1,730	780	1,200
18/08/2012				1,760	880	1,170
7/09/2012	7,200	4,900	9,000	2,200	990	1,440
4/10/2012				2,600	1,240	1,790
18/11/2012				3,400	1,640	1,840
19/12/2012	14,700	9,500	14,000	4,400	2,100	3,400
25/01/2012	12,700	8,600	15,500	3,500	1,720	2,300
28/03/2012	4,700	2,500	2,200	1,900	710	1,200
30/04/2012	11,000	7,500	7,000	2,900	1,200	2,000
Average	10,060	6,600	9,540	2,710	1,251	1,816
Average removal				**73%**	**81%**	**81%**

The Northland pond provided efficient removal of both solids and COD (73%, 81% and 81% removal for TS, VS and COD respectively) (Table 2). Despite the variability in influent (i.e., raw cow shed effluent entering the anaerobic pond) quality, (which was partly due to the grab sampling method), pond effluent (i.e., treated effluent leaving the anaerobic pond) solids concentration was low and relatively consistent throughout the year.

Table 3 Southland anaerobic pond solids and COD data

	Influent			Effluent		
Sampling date	TS g/m^3	VS g/m^3	COD g/m^3	TS g/m^3	VS g/m^3	COD g/m^3
6/07/2011				1,880	900	1,180
26/09/2011				1,760	1,160	1,660
18/11/2012				4,800	2,700	3,000
20/12/2012				2,600	1,360	2,300
26/01/2012				2,400	1,170	1,640
8/03/2012				2,300	1,200	1,690
Average				2,623	1,415	1,912

Table 4 Waikato anaerobic pond solids and COD data

	Influent			Effluent		
Sampling date	TS g/m3	VS g/m3	COD g/m3	TS g/m3	VS g/m3	COD g/m3
2/06/2011				1,220	570	700
18/08/2012				1,430	820	1,390
1/09/2012	8,100	5,000	7,400	1,860	1200	1,480
27/09/2012	8,300	5,300	5,900	1,930	1,180	1,800
21/11/2012	5,900	4,300	7400	2,100	1,100	1,740
20/12/2012	10,100	7,500	9,600	1,410	590	880
Average	8100	5525	7575	1658	910	1332
Average removal				**80%**	**84%**	**82%**

Due to sampling difficulties, no influent data from the Southland pond were available. However, the TS, VS and COD data of the Southland pond effluent analysis (Table 3) were quite similar to the Northland data (Table 2), indicating comparable treatment performance.

During the 9 month monitoring period the solids and COD concentrations in the influent and effluent and overall removal by the Waikato anaerobic pond (Table 4) were very similar to the values recorded for the Northland pond (Table 2).

In addition to the high solids and COD removal achieved by both the Northland and Waikato anaerobic ponds (and indicated for the Southland anaerobic pond) the volatile fatty acid (VFA) concentrations in the pond effluent from all 3 ponds measured in 2011 were very low (near detection limit for standard effluent VFA analysis – data not shown). This indicates that the ponds were not losing VS either as particulate or dissolved solids in the effluent or in the form of VFAs, suggesting a high solids retention and conversion to biogas within all 3 ponds.

The average CH_4 content of the biogas produced by the Northland, Southland and Waikato anaerobic ponds (measured monthly from September 2011 to April 2012 from Northland and Southalnd and September 2011 to December 2011 for Waikato) were 76.4%, 77.2% and 79.70%, respectively. These high CH_4 concentrations may be a reflection of a relatively moderate pond loading rate as well as algal growth within the upper layers of the pond water column, both of which can lead to biogas CO_2 re-dissolving from the gas space back into the pond water column under the field cover, resulting in an increase in the CH_4 content of the collected biogas.

The monthly total flow of CH_4 produced by the anaerobic ponds (Figs 6, 7, 8) were calculated by multiplying the temperature-corrected raw biogas flows with the average measured biogas CH_4 content. This value was then divided by the area of the gas collection cover (25 m^2) and multiplied by the anaerobic pond mid-depth area. This approach assumes that biogas production is uniform across the whole anaerobic pond area.

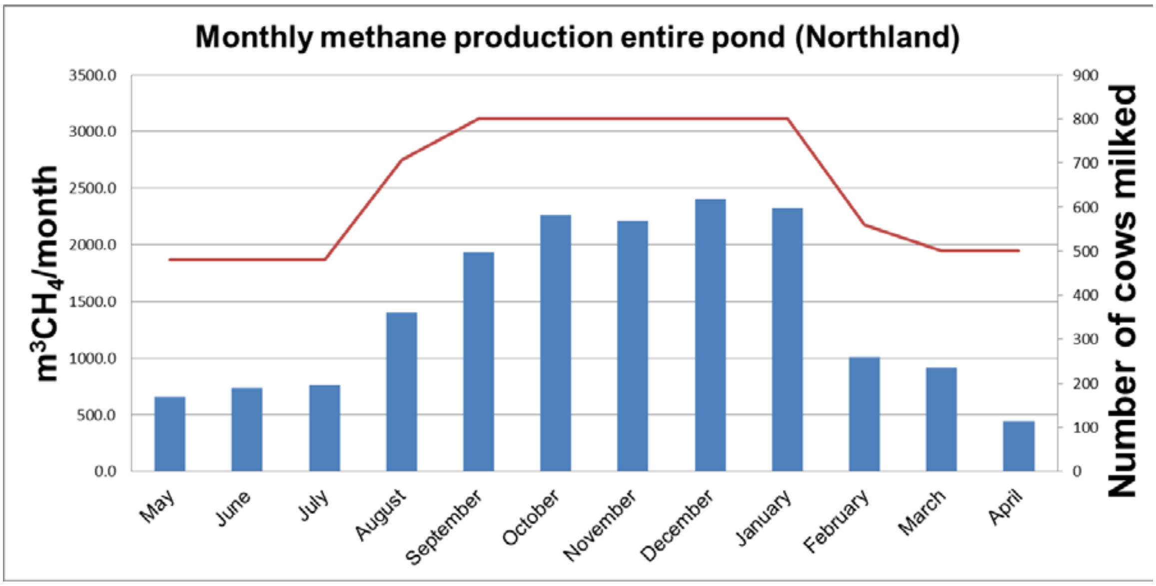

Figure 6 Calculated total CH_4 production from the Northland pond in relation to the number of cows milked (red line).

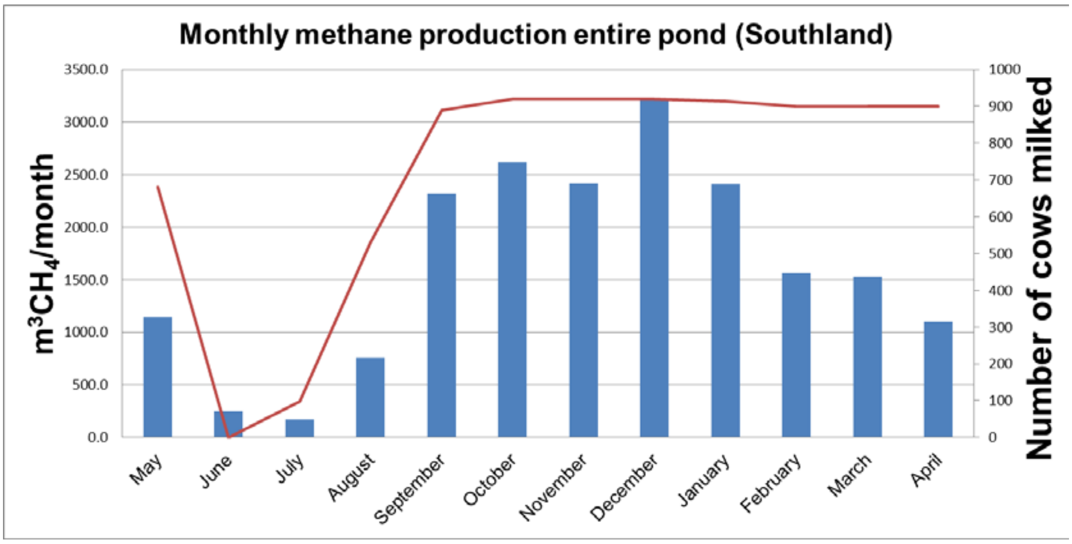

Figure 7 Calculated total CH_4 production from the Southland pond in relation to the number of cows milked (red line).
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Monthly CH_4 production from the Northland and Southland anaerobic ponds both varied markedly and broadly correlated with the seasonal variation in temperature. Temperatures of the sludge at the bottom of both ponds varied by ~10°C between winter and summer, while CH_4 production in the Northland and Southland ponds varied by 6-fold and 15-fold, respectively. The greater variation in CH_4 production from the Southland pond could be due to a combination of the lower operating temperature and the milking "dry season" in June and July when no effluent was added to the pond.

The summer (December) peak CH_4 production was higher for the Southland anaerobic pond than for the Northland anaerobic pond both in terms of total CH_4 production (Figs 6, 7) and CH_4 production per cow (~3.5 m^3 CH_4/cow/month compared with ~3.0 m^3 CH_4/cow/month for the summer milking herds of 920 cows [Southland] and 800 cows [Northland]). This indicated that, despite the lower temperature of the Southland anaerobic pond, anaerobic digestion in this pond was very efficient, and was probably digesting organic solids that had accumulated during winter.

The 9 month monitoring of CH_4 production at the Waikato pond (Fig. 8) suggests that, similar to Southland, a lack of CH_4 substrate during the milking "dry season" caused a greater reduction in pond CH_4 production than low pond temperatures.

Total annual CH_4 production from the Northland and Southland anaerobic ponds were calculated to be 17053 m^3 CH_4/year (11562 kg CH_4/year) and 19502 m^3 CH_4/year (13223 kg CH_4/year), respectively. For the 800 and 920 cows at the Northland and Southland farms, this equates to average anaerobic pond CH_4 emissions of 21.32m^3 (14.45 kg) CH_4/cow/year and 21.20 m^3 (14.37 kg) CH_4/cow/year respectively (assuming a CH_4 density of 0.68 kg m^{-3} at 15°C and standard pressure). These calculations were determined by combining CH_4 emissions from the mid-pond depth surface area by the number of cows being milked throughout the different months (see Appendix A).

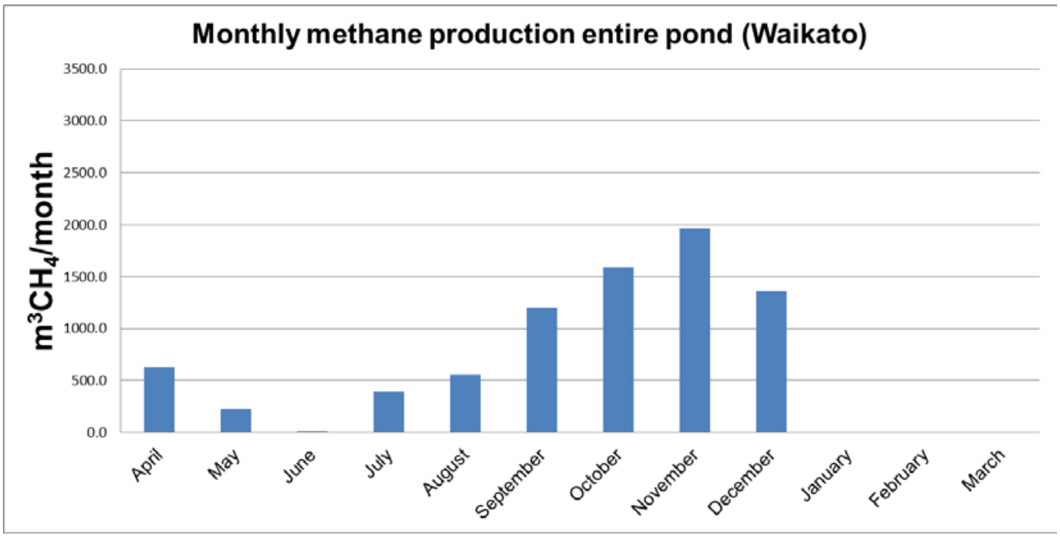

Figure 8 Calculated total CH_4 production from the Waikato pond, no data available on number of cows milked.

Interpretation of the Waikato data is more complicated since only a 9-month data-set is available. The 9-month data indicate a gross CH_4 production of 7933 m^3CH_4/year (5379 $kgCH_4$/year), or 11.33 m^3 and 7.68 kg CH_4/cow/year, based on a herd size of 700 cows. To extrapolate the 9 months Waikato data to a full year, the monthly distribution of gas production from Southland, a summer milking farm where a full years worth of data is available, has been used to determine an appropriate estimate. During February, March and April 2012 the Southland pond was producing 21.5% of the annual total biogas volume. Applying this factor to the Waikato data, resulted in a projected annual yield of 10,106 m^3CH_4/year (6,852 $kgCH_4$/year), or 14.44m^3 and 9.79 kg CH_4/cow/year.

The very good agreement between the annual CH_4 production figures for Northland and Southland indicates that for the given pond loading rates and operational regimes, the lower pond temperatures in Southland may have little effect on the overall biogas CH_4 production per cow or unit VS input. However, the more seasonal manure production in Southland does lead to a much wider seasonal fluctuation in CH_4 production, with higher peaks in summer and lower troughs in winter. Overall, the CH_4 emission yields from the ponds determined in this study were similar to yields determined by Craggs et al. (2008) and those reported in a New Zealand Agricultural Greenhouse Gas Research Centre-funded project completed prior to this research.

Assuming a CH_4 potential of 0.22 m^3CH_4/kgVS (as determined during the laboratory studies of this project in Objective 1), and a correction factor of 90%, reflecting poorer solids conversion under field conditions compared to laboratory conditions, the amount of solids entering the Northland and Southland anaerobic ponds annually per cow would be 107.7 kgVS/cow/year and 107.1 kgVS/cow/year, respectively. Assuming that a cow has an annual VS production of 1050 kgVS/cow/year (MfE, 2012), this would indicate that 10.3% and 10.2% of all VS excreted by the cows at the Northland and Southland farms respectively was collected and treated in the effluent ponds.

4.3 Anaerobic pond use across New Zealand dairy farms

Data from regional and district councils and DairyNZ showed that there are 12076 dairy herds in New Zealand in 2011–2012, compared with the 'New Zealand Dairy Statistics 2010–2011' (DairyNZ, 2011) figure of 11735 for 2010–2011. Most dairy farms are in the North Island, with Waikato and Taranaki containing almost 50% of total herds (Fig. 9). Canterbury and Southland have the most herds in the South Island (about 1000 each) but only represent about 15% of New Zealand's total herd number. Gisborne and Nelson contain the lowest herd numbers (4 and 1, respectively).

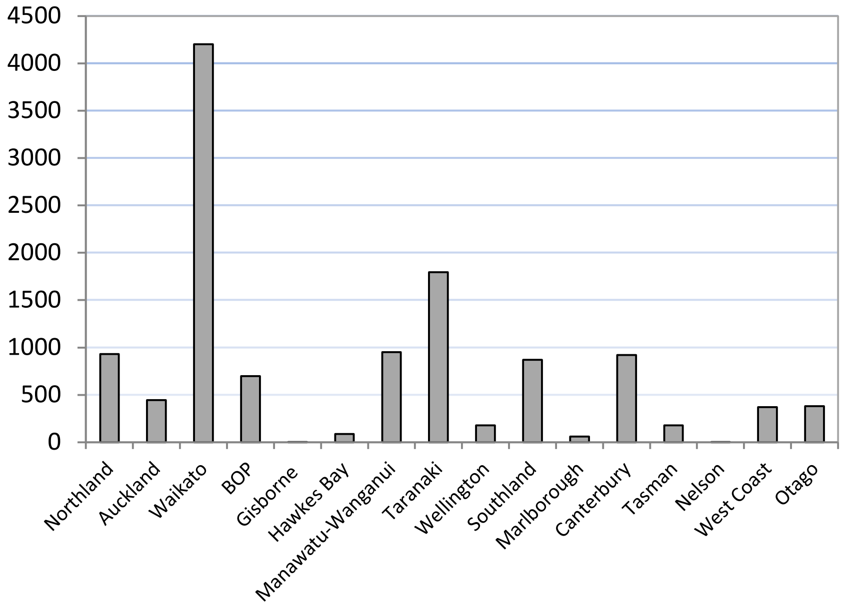

Figure 9 Dairy herd numbers through New Zealand on a regional basis from 2010/11 (from DairyNZ, 2011 and council information).

Herd sizes are greatest (>600) in the Canterbury, Gisborne, and Hawkes Bay regions (Fig. 10). However, of these, Canterbury is the only sizeable dairying region (with a herd number greater than 90). By contrast, Taranaki is a sizeable dairying region with over 1700 farms, yet the average herd size on these farms is very low (277) compared with the New Zealand average (426).

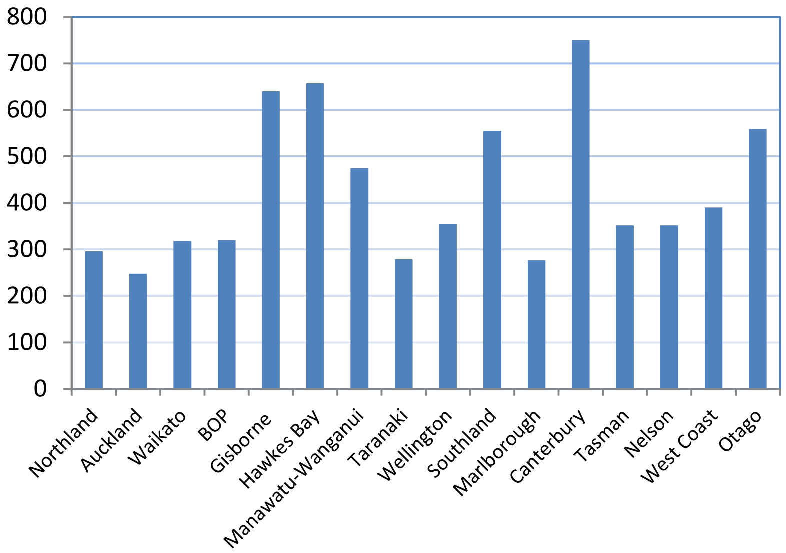

Figure 10 Average herd sizes for NZ regions (from DairyNZ, 2011 and council information).
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The Waikato region contains the greatest dairy cow numbers on a regional basis (nearly 29% of NZ's total dairy population). In terms of cow numbers Canterbury is the second most important dairying region in New Zealand, with approximately 15% of the nation's dairy population (Figure 11). This is despite the fact that only 8% of New Zealand's dairy herds are in this region and reflects rather the large herd sizes in Canterbury.

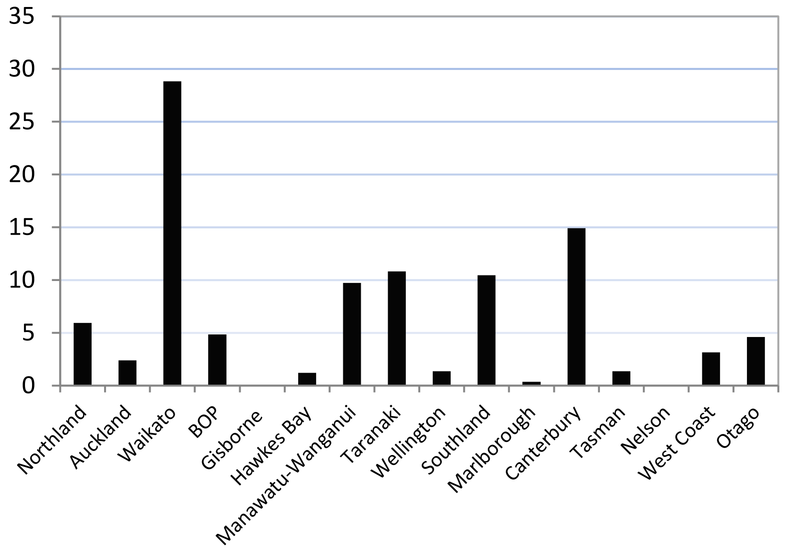

Figure 11 Percentage of New Zealand's total dairy cow population in each region (from DairyNZ, 2011 and council information).

Figure 12 shows the breakdown of anaerobic pond use in the various regions of New Zealand. The Waikato clearly has far more anaerobic dairy effluent ponds than the other regions (approximately 35% of the nation's known total dairy effluent ponds). Of the significant dairying regions (i.e., greater than 100 herds), Canterbury has the lowest proportional use of effluent ponds with, 73% of farms irrigating effluent directly to land from a sump.

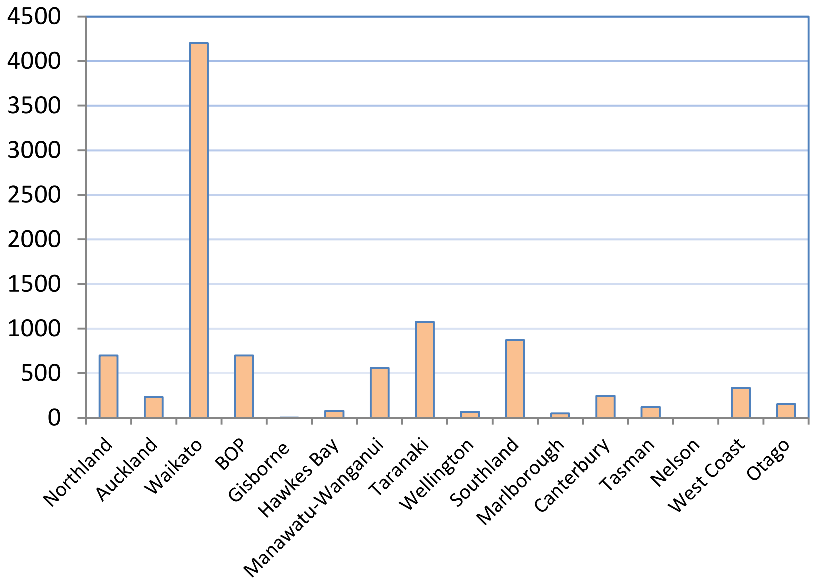

Figure 12 Number of anaerobic dairy effluent ponds in NZ regions (from council and DairyNZ information).

Overall, 78% of New Zealand's approximate 12 000 dairy farms have some form of anaerobic effluent pond. However, when using this information to estimate pond CH_4 emissions on a national scale, effluent pond usage per cow should be used rather than on a per farm basis. This is because some regions have relatively large herd sizes compared with farm numbers. For example, in Canterbury, effluent pond usage is very low, which effectively reduces the average effluent pond usage rate across New Zealand. On this basis, effluent from approximately 73.5% of New Zealand's dairy cows enter a pond, while effluent from the remaining 26.5% is irrigated directly on to land from a sump or small holding tank.

It is important to note that anaerobic pond usage on New Zealand dairy farms is increasing. For example, in 2011, the ECan reported that 171 farms (17%) in the region had some form of effluent pond (i.e. permit for storage > 1week). By 2012, this number had risen to 248 (27% of all farms in the region). Increased pond use is not restricted to certain regions. Staff from Tasman District Council noted that all dairy farms in New Zealand are being encouraged to increase effluent storage capacity. In effect, nearly all New Zealand dairy farms will have some form of storage pond in the next few years and, consequently, the contribution of CH_4 emissions from this source to the national Inventory will also increase.

4.4 Synthesising the data to estimate methane emissions from New Zealand's anaerobic dairy effluent ponds

The CH_4 potential values for dairy effluent determined in Objective 1 can be combined with the effluent pond usage data from Objective 3 to derive an experimental estimate of CH_4 emissions from dairy effluent ponds across New Zealand. In this approach it is assumed that the CH_4 yield from effluent ponds is not affected by temperature, which was verified by the field data obtained from Northland and Southland reported in Objective 2. This experimental approach of estimating CH_4 emissions from dairy effluent ponds on a New Zealand-wide basis was performed via a sensitivity analysis which incorporates uncertainty surrounding the key parameters involved in CH_4 production. The details of the analysis are presented in Table 5.

Table 5 Parameters considered in the sensitivity analysis[a]

	Unit	Medium	Low	High	Current (i.e., value used in inventory)
BMP[b]	kg CH_4/kg VS_{added}	0.150	0.137	0.185	NA
DMI[c]	kg/cow-yr	4,700	4,000	5,400	4,000
$\%_{VS}$[d]	-	0.88	0.86	0.90	NA
U[e]	kg VS/cow-d	0.3	0.25	0.35	0
$\%_f$[f]	-	0.74	0.74	1.00	1.00
MCF[g]	-	0.74	0.69	0.9	NA
VS[h]	kg VS/cow-yr	1019	899	1349	NA

a) Unless otherwise notified, methane emissions were calculated based as:

$$\mathrm{CH_4(Gg\,CO_2-eq,2010)} = 4.68 \cdot \left[DMI \cdot \%_{vs} \cdot (1-0.78) + U \cdot 365\right] \cdot 0.06 \cdot \%_f \cdot BMP \cdot MCF \cdot 21$$

Where 4.68 is the number of dairy cow in 2010 (millions, from NZ Govt. 2012); *DMI* is the dry matter intake (kg/cow-d); $\%_{VS}$ is the VS content of FDM (faecal dry matter); *U* is the rate of urine generation; 0.78 is the feed digestibility; 0.06 represents the fraction of manure discharged to effluent ponds for the milking cow population, based on data from Ledgard & Brier, 2004; $\%_f$ is the fraction of farms where manure effluent is treated in anaerobic ponds; BMP is the biochemical potential of methane; *MCF* is the methane conversion factor (i.e., how much of the *BMP* of manure is actually used under field conditions); and 21 is the warming potential of methane (MfE, 2012).

b) The base value is the average experimental BMP from this study; the high and low values are based on IPCC guidelines for Oceania (0.24 m^3/kg VS added ± 15%, density of 0.67 kg/m^3).

c) Base value according to Lassey et al., 1997; low value according to NZ GHG; high value selected to set base value as median of range

d) Base value according to Tomlinson et al. (1996) and Nennich et al. (2005); high and low value based on the variance of 2.6% reported in this study for manure.

e) Base value according to Vanderholm, 1984, variance based on MPI staff pers. comm.

f) Base value based on survey; high value based on trends in next few years (pers. comm.)
g) Base value based on IPCC guidelines for open anaerobic pond at 15°C; low value based on IPCC guideline at 11-12°C; high value based on simulations at 15°C.
h) In this particular simulation, the base value of the total amount of VS produced per cow per year was calculated as $\left[DMI \cdot \%_{vs} \cdot (1-0.78) + U \cdot 365\right]$ using the base values listed in the table; the low and high values were based on IPCC guidelines (3.5 kg VS/cow-d ± 20% for a 500 kg cow in Oceania) adjusted to a 440 kg cow.

The parameters in Table 5 were modelled to assess how NZ-wide CH_4 emissions from dairy effluent ponds respond to uncertainties surrounding the key variables involved in CH_4 production. The medium or baseline values used to assess pond CH_4 emissions yielded a CH_4 production of 489 Gg CO_2-e for 2010 (Fig. 13). Following the most conservative approach, where the CH_4 conversion factor (MCF) for dairy manure is very low (0.69), produced a CH_4 yield of 424 Gg CO_2-e for 2010. At the other end of the scale, we can see that CH_4 emission yields dramatically increase from the baseline value when upper ranges of VS loads entering ponds and the number of farms with effluent ponds are factored-in. These factors clearly strongly influence CH_4 production and uncertainty surrounding them needs to be resolved through further research.

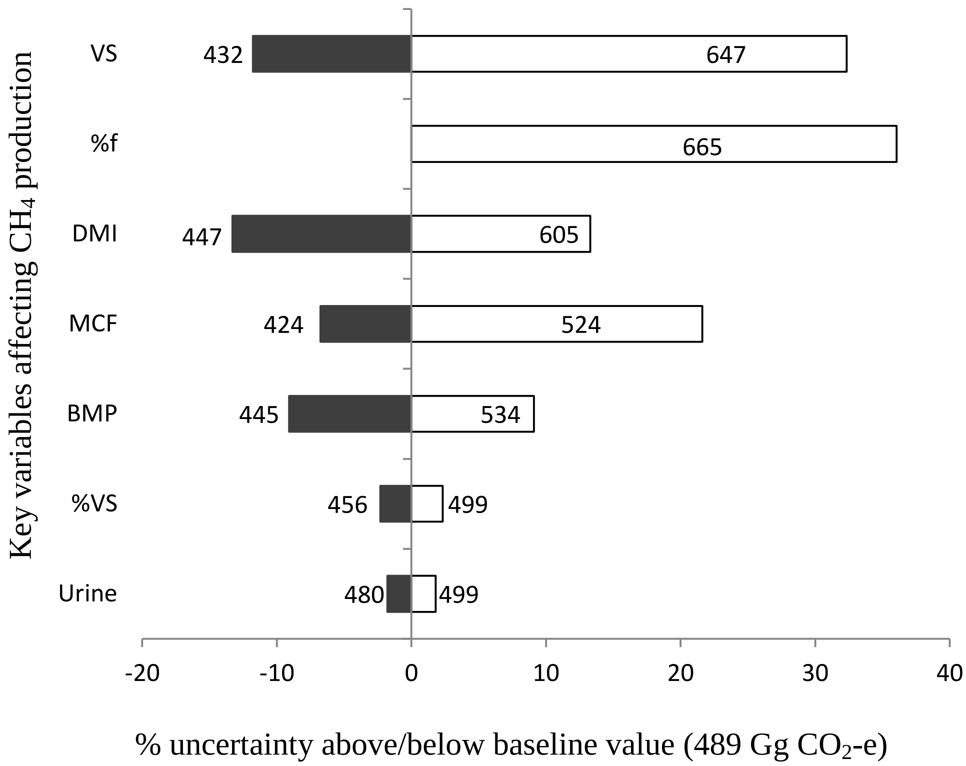

Figure 13 Experimental determination of CH_4 yields (Gg CO_2-e) from dairy effluent ponds NZ-wide in 2010 as a function of uncertainty around the key variables involved in CH_4 production.

In addition to experimentally-derived values, it is also possible to derive a field-based estimate of CH_4 emissions from New Zealand dairy effluent ponds, using the CH_4 pond surface flux data measured in Objective 2. The average annual CH_4 production rate for the monitored Northland, Waikato and Southland farms was 13.45 kg CH_4/cow/year. The annual CH_4 yield (again, based on 2010 cow numbers) can then be calculated as follows:

Eqn 1 – Annual field-based CH_4 yield (based on 2010 cow numbers) for all New Zealand dairy effluent ponds (Gg CO_2-equivalents) = 13.45 kgCH_4/cow/year × 21(GWP) x lactating dairy cow population × proportion of cows who's effluent goes to a pond during milking/1000000

Based on this calculation, Equation 1 gives an annual CH_4 production of 972 Gg CO_2-e for New Zealand dairy effluent ponds (Fig. 14). This equates to >10% of dairy enteric emissions reported for 2010, and is clearly much greater than the production rate derived from the experimental sensitivity analysis. There are a number of possible factors accounting for this discrepancy. Firstly, the average CH_4 yield derived from the 3 field covers may overestimate typical emissions from NZ dairy effluent ponds. However, this is unlikely because the variability in CH_4 production between each site was remarkably low (standard deviation = 15% of the mean value). Moreover, even if the CH_4 production from the site with the lowest emissions (11.53 kg CH_4/cow/year) is used in Equation 2, a NZ-wide annual CH_4 production of 833 Gg CO_2-e is calculated, which is still higher than the experimental yield. This suggests that the experimental method is under-estimating emissions, rather than the field method overestimating them.

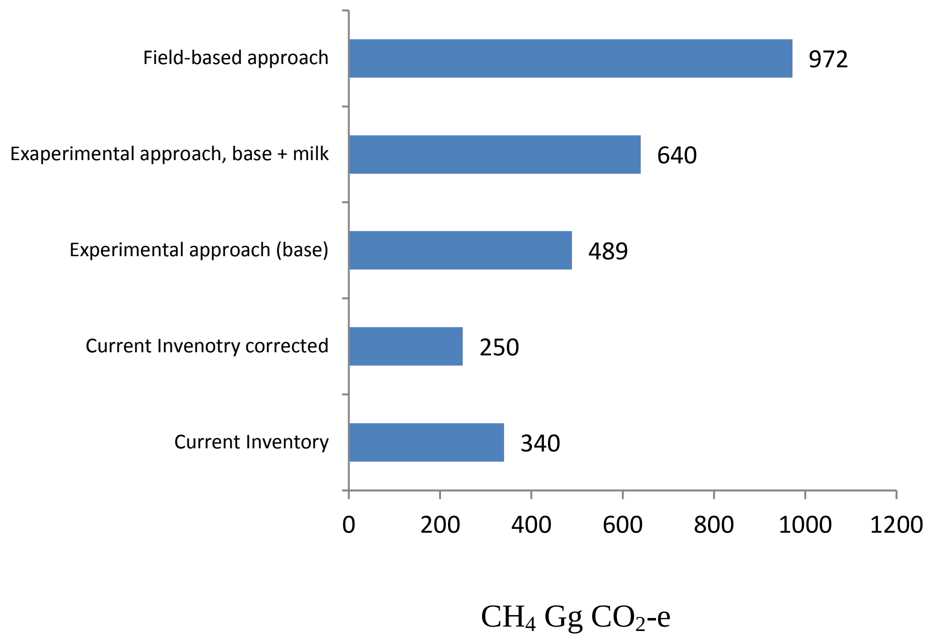

Figure 14 Methane yields from dairy effluent ponds NZ-wide in 2010, as determined by the experimental approach and the field-based approach. The effect of milk waste entering ponds on CH_4 production is shown, as is the current estimate of CH_4 emissions in the Inventory and the corrected emission yield factoring-in 73.5% effluent pond usage.

One factor that undoubtedly contributes to CH_4 emissions from dairy effluent ponds that was not accounted for by the experimental method is spilled or waste milk that enters effluent ponds from the milking shed. Here, a simplistic calculation is presented to show the effects that a small volume of waste milk entering ponds can have on CH_4 production. A NZ study showed that around 1% of all cattle were removed from milk supply due to residual effects from antibiotics treatment (Petrovski et al., 2009). Assuming a quarter of this "sick milk" cannot be used for animal consumption, a total of 43,350 m^3 of sick milk waste is generated annually (based on a yearly milk production of approximately 3.8 m^3 per lactating cow, Saka et al., 2009). Additionally, if we assume the amount of milk discharged from piping rinses and purges is approximated at 30L/day for each farm for 300 milking days (Pers. comm.), this amounts to 105,000 m^3/yr. Finally, based on national average milk contamination rate of one × 3 m^3 tank every 2 years (Pers. comm), contaminated tanks would equate to approximately 17,600 m^3 of waste milk each year.

The BMP of raw milk is very high and can be conservatively estimated to be 46.7 kg CH_4/m^3 milk (based on milk COD of 220 g/L and a biodegradability of 90%). Factoring this CH_4 potential into the total waste milk entering effluent ponds yields a CH_4 production of >150 Gg CO_2-e, using population and FDM intake data from 2010 for comparison purposes. This assessment of the impact of milk waste on CH_4 emissions is only an estimate but it clearly shows that milk could account for a significant proportion of CH_4 emissions from dairy effluent ponds.

Another factor that may account for the discrepancy between the experimental and field-derived CH_4 emissions is the possibility that the amount of manure deposited on the milking shed holding pad is currently underestimated. In the national GHG Inventory, and in this report, it is assumed that over a year 6% of a typical lactating dairy cow's manure is deposited on the milking shed pad (Ledgard & Brier, 2004). However, there is some evidence to suggest this percentage is higher. For example, in our study we measured solids loading rates going into an effluent pond by collecting manure in small grids on the milking shed holding pad. Our results indicated that about 15% of daily manure was deposited on the holding pad. This result only applied to three days of sampling for one specific farm. Yet, even if the current estimate were increased from 6% to 8%, this would result in a 1.3 × increase in CH_4 emissions from ponds using the experimental approach. Clearly, this is an important factor influencing CH_4 yields from dairy effluent ponds and requires further research.

Overall, we believe the field-based method is the most accurate approach for estimating CH_4 emissions from New Zealand dairy effluent ponds, until a full assessment of factors affecting the experimental yield of CH_4 from ponds is completed. While we acknowledge that the field estimate is based on three pond studies, the field measurements represent a much more rigorous basis on which to scale-up national dairy effluent pond emissions than the single study used in the current GHG Inventory.

We consider the CH_4 yield derived from the experimental approach should match closely with the field-based approach when more input data on manure loading rates to ponds and the effect of waste milk on CH_4 emissions become available. The equation for estimating CH_4 emissions from dairy effluent ponds should take the form:

Eqn 2 – M(DEP) = (∑Organic solids entering ponds) × ∑MCF

Where, M(DEP) = methane from dairy effluent ponds
MCF is methane conversion factor of the organic solids entering ponds (e.g., manure, milk waste, feed residues).

This revised equation should provide a much improved estimation of nation-wide emissions from dairy effluent ponds. Once this more robust estimate is made, it will become clearer which technologies will be most suitable for mitigating CH_4 emissions from effluent ponds. Currently, based on Inventory data, it is assumed that CH_4 yields from dairy effluent ponds are too low to make energy recovery economically-viable. However, our revised preliminary estimates have shown that these emissions are likely to be much higher than the current national inventory indicates. Therefore methane capture using retrofit pond covers may already be economically viable for farms of a certain size, depending on feed-pad use and the local value of the biogas energy (e.g. for heating/cooling and/or power). Alternatively, methane emission mitigation could be achieved using retrofit pond covers for methane capture and combustion using a flare; methane oxidizing biofilters on or beside the pond (e.g., Pratt et al., 2012); or pretreatment solids removal using solids separators or weeping walls. These options will become more important if agriculture becomes subject to the ETS or some other GHG regulation framework, and a comparison of costs versus GHG mitigation and other environmental benefits would be very useful.

5 Future considerations

Results from our investigation indicate that the national GHG Inventory is currently underestimating dairy effluent pond CH_4 emissions by a factor of 1.7 to 4. However, the scope of the current research needs to be expanded beyond the objectives funded for this study, to test our hypotheses on why there is a discrepancy between our experimental and field-based emission estimates. The new research first needs to assess the amount of manure that enters dairy effluent ponds from the milking shed holding pad. This could be done by sampling manure volumes and total and volatile solid deposition rates on milking pads at various farms across the country. The data can then be compared to average dry matter intake and faecal dry matter values derived for dairy cows in the national Inventory. This analysis will indicate whether or not the current 6% estimate for manure deposited on the milking pad is accurate.

Second, the volume and CH_4 production potential of milk waste entering dairy effluent ponds needs to be determined. This could be done by laboratory testing of the CH_4 yield of milk stored under anaerobic conditions. Data on milk spillage and waste could be collected through farm surveys and from an assessment of the literature. Future research should also address CH_4 emissions from deferred storage irrigation ponds.

In addition to the above research, the contribution to dairy effluent pond CH_4 emissions from concrete feed pads needs to be determined. The current Inventory does not take these structures into account in CH_4 production estimates. However, as DairyNZ staff note, sealed feed-pads are being increasingly adopted on New Zealand farms, and in many cases the effluent is discharged to a pond. The period of time that cows stand on feed pads is not known, but it is likely to be similar to the time they spend on the milking shed pads. These structures are therefore an additional potential source of CH_4 emissions. Farm surveys and interviews with DairyNZ staff could be used to accurately establish the extent of feed pad use on New Zealand dairy farms.

Finally, dairying practices are continually changing. Not only are rapid changes occurring from the increased use of effluent ponds and feed pads on farms, but also long-practiced year-round pasture grazing may also be about to change. In a recent ‘call-for-proposals’ on research into land-use change, the Ministry for Primary Industries (MPI) noted that

"Currently there is widespread interest in removing animals from pastures and placing them on stand-off pads or more permanent housing." If this shift in animal management occurs, it would have an enormous impact on the way that dairy effluent is managed. The time that cows spend on sealed surfaces would increase, so that more manure would need to be treated by effluent ponds, resulting in higher CH_4 emissions. If a much higher proportion of the total daily dairy cow waste production is collected, and manure management practices are not changed, manure CH_4 emissions have the potential to equal the current main agricultural GHG sources of enteric methane and pasture nitrous oxide emissions. Fortunately, the technology approaches mentioned above could mitigate these potential future sources of farm GHG emissions, and options to capture and recover the energy from manure derived methane have both environmental and economic benefits that could see them readily adopted by farmers. Therefore implementation of methane emission mitigation and use technologies should be considered as an integral part of future dairy farm effluent management.

6 Conclusions

- The current New Zealand Inventory is underestimating CH_4 emissions from dairy effluent ponds.
- In this research, a total experimental CH_4 yield of 489 Gg CO_2-e from dairy ponds was calculated for 2010 using the CH_4 conversion rate for dairy manure solids derived in Objective 1 and by scaling-up to the proportional usage (i.e. 73.5%) of effluent ponds on dairy farms across New Zealand (determined in Objective 3).
- This CH_4 yield is 2 × higher than the corrected 2010 Inventory estimate (250 Gg).
- Combining the field-measured pond CH_4 flux data from Objective 2 with effluent pond usage rates across New Zealand yields a total CH_4 estimate of 972 Gg CO_2-e, which is almost 4 × higher than the corrected 2010 Inventory value.
- The difference between the experimental and field-based yields (both of which are considerably higher than the current Inventory estimate) may relate to a number of factors outside the scope of this study.
- These factors include: 1) additional organic materials entering ponds, such as milk waste, and 2) a higher volume of manure entering ponds than currently reported. Both of these factors were not accounted for in this study's experimental CH_4 calculation but were inherently factored into the field-based calculation.
- The increased use of feed pads and standoff pads on New Zealand dairy farms means that CH_4 emissions from ponds are likely to be even higher than reported in this work.

7 Acknowledgements

We thank MPI for provision of funding for this work, and to staff from New Zealand regional councils, DairyNZ and AgResearch for their time and information.

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APPENDIX A – Farm monitoring methane emission calculation

The field methodology for calculating effluent pond methane emissions is based on:

- The experimental cover area of 25m^2 (5m x 5m)
- The assumption that a representative area of the pond is monitored.
- The qualified assumption that the vast majority of methane productions happens in the first (anaerobic) pond.
- Real time (15 min interval) raw biogas flow data (logged from flow meter)
- Real time gas temperature data (15 min interval) (logged form thermocouple)
- Average biogas methane concentration (76.4%CH_4 for Northland - 77.2%CH_4 for Southland) (the arithmetic average of monthly biogas quality monitoring)
- The pond mid-depth area (Note: this is the average between pond surface area and pond bottom area for regularly shaped ponds) as the basis for realistically extrapolating 25 m^2 measurements to the whole pond, accounting for fringe effects (1,000 m^2 for Northland, 1050 m^2 for Southland).
- Dairy herd size (Cow numbers: 800 for Northland, 920 for Southland)

Calculation

Step 1: Temperature correction

The logged data of biogas flow provides 96 individual data points for each day (Biogas flow is logged on 15 min intervals). Raw data logger data was copied into a Microsoft Excel table for further processing. The 96 data points of biogas flow are temperature corrected with the 96 corresponding data points for gas temperature according to the equation of Gay – Lussac:

$$V \sim T \qquad \frac{V}{T} = \mathrm{const} \qquad \frac{V_1}{V_2} = \frac{T_1}{T_2}$$

To get the temperature corrected biogas volume at standard conditions (15^{o}C and 1013 mbar). Since gas / air pressure variations over the course of the monitoring period were only marginally different from the standard pressure of 1013 mbar, a standard pressure correction according to the equation of Boyle-Mariotte was not conducted.

Step 2: Aggregation and methane correction

The 96 temperature corrected biogas volumes for each day were summed up (in Excel) to yield daily, weekly and monthly raw biogas totals. These totals were then multiplied with average biogas methane concentrations (76.4%CH_4 for Northland - 77.2%CH_4 for Southland - analysed by monthly sampling) to get daily, weekly and monthly temperature corrected methane totals.

Step 3: Extrapolation

The daily, weekly and monthly methane totals represent the flow from 25 m^2 of pond surface under the experimental cover(s). To calculate the total pond methane emissions (e.g. per month) the monthly total was divided by 25 m^2 and multiplied with the respective pond mid depth area (1,000 m^2 for Northland, 1050 m^2 for Southland). This provided results for total monthly pond methane emissions per farm.

Step 4: Annual per cow emissions

By summing up May to April monthly methane totals per pond (farm), total annual methane emissions were calculated. These were then divided by the average herd size of each respective farm (800 for Northland, 920 for Southland) to calculate average pond methane emissions per cow per year.

Step 5: Calculation of VS collection per cow

By dividing the calculated pond methane emissions per cow per year with the experimental BMP factor (determined in the lab as 0.22 m^3 CH4/kgVS) the kg VS collected by the pond system per cow per year can be estimated. Comparison of this with the assumed 1050 kg VS excreted as manure per cow per year indicates that ~10% of the total manure VS was collected in the pond system and digested to methane.