AMPC

AUSTRALIAN MEAT PROCESSOR CORPORATION

FINAL REPORT – Organic waste management at abattoirs

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Table of Contents

Project 1: Assessment of the requirements to treat, store, or otherwise transform paunch into a useable product for on farm use and assess application rates

1.0 Executive Summary

The focus of this project was to assess the requirements to treat, store, or otherwise transform paunch into a useable product for on-farm use. The aims of the project were twofold: (i) to validate the criteria for paunch stabilization, and (ii) to determine the application rates for on farm use.

This work comprised three sets of interconnected experiments, which were conducted under controlled conditions of temperature and soil moisture both in the laboratory and glasshouse. Samples of paunch of varying ages (fresh: 2-4 weeks, semi-composted: 6 weeks, and fully composted: 12-16 weeks) were sourced from two abattoirs. The results provided important information regarding: (1) Risk of weed contamination, (2) Agronomic performance, and (3) Nutrient release characteristics of various aged paunch.

The following project outcomes resulted from the work:

- **Risk of weed contamination:** The number of plantules germinated after three weeks reported a value of zero in all daily observations and treatments. This suggested low (or no) risk of weed contamination in soil amended with paunch whether fresh or at varying degrees of composting.

- **Stabilisation period:** Under the experimental conditions of this study, the six week-old compost showed relatively higher agronomic performance compared with all other paunch types. Thus, a six-week stabilisation period may be suggested as reference for paunch, and may be used as guidance until further studies are undertaken.

- **Land application rates:** The experimental work suggested no agronomic benefit when paunch-N application rate was increased from 150 to 300 kg per ha. Above that rate, paunch nitrogen use-efficiency (NUE) decreased significantly. Therefore, a preliminary recommendation is made for land application rates in grass crops not to exceed 150 kg per of paunch-N. This recommendation requires validation under field conditions, and for a wider spectrum of crop and soil types than that used in this study. The following results for NUE (relative to urea-NUE) were recorded, which varied depending on paunch source:

    - Fresh paunch (<4 weeks): between 20% and 25%,
    - Semi-composted (6 weeks): 40%,
    - Fully composted (12-16 weeks): between 15% and 40%.

- **Nitrogen fertiliser replacement value (NFRV):** Average NFRP of paunch applied to grass was estimated to be 40±17% across all types of paunch and rates. For different paunch types, NFRV reported the following mean values (±SD): 39±19.8% (2 weeks), 35±15.5% (4 weeks), 56±19.3% (6 weeks), 19±17.5% (12 weeks), and 52±13.6% (16 weeks), respectively. Value range of NFRV of paunch within this study was generally higher than those reported in the literature for organic materials applied to grass under field conditions; for example, farm yard manure (range: 37-50%), cattle slurry (range: 10-39%), and composted household waste (<10%).

The following areas have been identified as knowledge gaps and therefore merit a research priority. This work is required to further inform soil-, climate- and crop-specific land application rates, optimise agronomic performance and minimise environmental concerns:

1. The criteria for stabilisation of paunch during the composting process based on carbon maturity levels of the organic material may be more appropriate than an approach based on fixed composting time. This will allow for greater consistency in composted paunch used for land application by capturing seasonal effects of weather on microbial activity and carbon dynamics within compost piles, as well as differences in composting techniques and paunch sources across the industry,
2. The risk of pathogens needs to be determined based on the guidelines reviewed in this report,
3. To determine the effect of paunch on soil carbon dynamics and carbon sequestration in soil, and associated effects on nutrient dynamics, particularly nitrogen, including laboratory and medium- to long-term field studies, and modelling approaches that capture such effects on soil responses and crop productivity,
4. To investigate the effect of paunch on greenhouse gas emissions, including surface application (likely grass based and arable cropping systems under zero-tillage) and shallow incorporation (conventional and minimum tillage cropping systems), respectively,
5. To determine the optimum timing of application for both grassland and arable cropping systems to maximise nutrient recovery in crop biomass and yield, and the optimum number of splits within a calendar year or growing season,
6. To investigate the logistics, and agronomic and economic implications of applying paunch to supply a proportion of the nutrient demand by the crop and the balance with a mineral fertiliser source whether as a blended material (balanced organo-mineral fertiliser) or in split applications. This is based on the fact that paunch will likely provide a relatively low, although sustained, supply of nutrients to crop (slow release source) and possibly over the rotation, whereas the mineral fraction will provide a shorter-term supply of nutrients. This needs to be determined in conjunction with Recommendation (3): Optimum timing for field application,
7. There is a requirement to improve the physical quality of paunch (consistency, particle size, size distribution, density properties, and moisture content) to enable field application with standard fertiliser spreading equipment. For this, a recommendation is made to investigate the feasibility of granulating or pelletising paunch as well as the energy requirements for drying of the organic material. Where feasible, granulation would be the preferred option due to aerodynamic properties, and greater control over the particle size range required for efficient field spreading, reduced segregation and breaking of particles. Compared with current practice for field application such a development will:
    a. Allow for improved field operating efficiency and reduced costs of field application, including labour,
    b. Allow for improved distribution uniformity, and therefore improved nutrient use-efficiency by the crop and reduced risk of nutrient losses to the environment,
    c. Improve logistics both at farm and field levels. Bagging of granulated (or pelletised) paunch will significantly improve handling, storage, facilitate dosage for field spreading. A drier material in the form of granules or pellets will reduce cost of transport and may enable expansion of current land-bank available for recycling (Spence et al., *In preparation*),
    d. The above should also consider mechanisation requirements for field spreading (equipment, settings, and techniques), including adjustments needed to mitigate traffic impacts on soil, and soil compaction-related greenhouse gas emissions,
8. There is also a requirement for field validation of the findings derived from the laboratory and glasshouse studies undertaken within this work, which needs to be continued in order to acquire a more complete dataset than that presented in this report,

9. There is a need to perform detailed economic analyses assessed against alternative options available for disposal of paunch, and conduct contingent valuation studies to determine farmers' willingness to pay for enhanced quality paunch-derived materials. Such analyses should be undertaken as a cost reduction (or cost avoidance) strategy, and may require the final product to be partially subsidised to encourage uptake by farmers,
10. This study focused on primarily on grass response to paunch, and soil nitrogen and phosphorus dynamics. Therefore, further work is required to understand soil dynamics and crop effects of secondary nutrients, including potassium, calcium and magnesium. This is an important practical consideration given relatively high (≈7:1) paunch-to-fly ash ratios used in the process,

The nitrogen fertiliser replacement value (NFRV) of paunch reported in this study has been derived from (short-term) glasshouse experiment using pots, and therefore requires validation in longer-term trials under field conditions. A similar approach to that employed for paunch nitrogen may be applied to provide estimates of phosphorus fertiliser replacement value of paunch.

2.0 Introduction

Abattoirs currently undertake one of several options to address paunch waste (PW) management, including:

1. Removing paunch and other solids off site
2. Composting material on-site and used on-site
3. Composting material on-site and used off-site

In the case of house-locked abattoirs where land space is not available composting or processing of paunch is not performed on-site. In these situations, paunch is removed off-site to a licensed premise which attracts a cost of $20 - $40 per cubic metre in gate fees and transport. The paunch is then mixed with other bulking agents and sold as either bulk soil conditioner or bagged compost. Essentially, the benefits of the nutrient-rich material are lost to the farming community because the end use is for domestic gardens only. Given that there are no guidelines/standards regarding best practice of PW management, the inherent challenges lie in how to get the paunch material back to the farms while minimizing costs.

One Australian abattoir has proposed one option which includes firstly holding the paunch (including other yard solids) on site for 1-2 weeks and then transporting the material via a covered and sealed tipper to a suitable property for up to 3 months before turning into the soil for use as a soil conditioner. A Beneficial Use Agreement (BUA) has been developed, however, further work to qualify particulars surrounding the requirements of PW management and handling are required. A previous report (PRENV.023) has assessed contaminants in waste solids from meat processing waste streams. However, further work is required to determine whether this provides sufficient information to satisfy the conditions of a BUA for handling paunch. Furthermore, there is a necessity for fundamental work to be carried out on two central issues, namely: (i) validating the criteria for paunch stabilization, and (ii) determine the application rates for on farm use.

This project sets out to firstly develop criteria around measuring the stability of PW and how to assess potential risks or harm from on-site storage and on-or off-site farm use due to risk of pathogens and/or seed germination. Secondly, investigations into land application rates will be performed to determine optimal strategies for PW as a soil conditioner.

There has been extensive work conducted on the beneficial use of paunch as a compost material; however, little is known about the usefulness of paunch in other decomposition states for on farm soil application (raw through to composted).

This study provides preliminary findings for a 4 month study which assessed the potential risks due to germination and land application rates. It is therefore limited in its ability to determine the beneficial use of land application over long term use. This is important in assessing the benefits of improving soil carbon and the impact on soil microorganisms, moisture retention and the increase in crop productivity. Whilst a preliminary assessment of the fertiliser replacement value of paunch has been made, long term studies will provide a more accurate indication of the value proposition to industry in terms of avoided costs due to decreased fertiliser use and disposal via gate fees.

2.1 Overview of previous waste solids literature

Table 1 provides a summary of best practice technologies and some commentary on previous work informing best practice treatment of organic solid wastes (PRENV.023a "*Assessment of contaminants in waste solids from meat processing wastewater streams*"). In summary, organic solid wastes produced from meat processing are eminently suitable to biological treatment processes. Due to their high moisture content, they are not particularly suitable for thermal energy recovery processes without extensive dewatering, which is typically uneconomic. Composting is the most commonly used.

Table 1: Review of treatment options for organic waste (from PRENV.023a "Assessment of contaminants in waste solids from meat processing wastewater streams").

DISPOSAL METHOD	SUITABLE FOR	COMMENTS
Composting	All organic solids	Composting is by far the most accepted method for treating and recycling nutrients present in all organic wastes from meat processing. Several techniques may be utilised but all produce a stable final material that can be sold as a soil conditioner or ingredient in a potting mix. However the value of the compost may not fully recover the cost of production. The main problem encountered is odour complaints from neighbours in sensitive areas.
Dry composting	Dead animals	Slaughter and boning wastes The pile may need to be covered to protect from the elements and discourage scavengers. A further composting process may need to follow to produce a usable product.
Anaerobic lagoons	Paunch solids Aerobic treatment sludges	The use of an anaerobic lagoon will digest about one third of the paunch material but the lagoon will silt up more rapidly requiring expensive dredging and disposal of the sludge.
Anaerobic digestion	Paunch contents Manure	This is a more sophisticated form of an anaerobic lagoon where the waste is digested in a sealed stirred tank. Biogas is produced (approx. 60% methane) which may be flared off or used as a fuel. After 10 – 30 days the solids are separated from the liquid and further stabilised or applied directly to land.
Surface spreading	Paunch contents Manure Anaerobic pond sludge	Although widely used in the past and inexpensive it will now require a permit. It is not preferred as there are environmental concerns as well as the risk of distributing weed seeds.
Sub-surface Injection	DAF sludges Paunch contents Aerobic treatment sludges	Direct soil injection can be practised with the approval of the EPA. It has the advantage of reducing the fly problem but the long term effect on the soil should be monitored.
Ensilage	Paunch contents	Trials have been conducted in the U.S. to produce a cattle feed but paunch has a low feed value and the cost of production and possible negative publicity discourage the process.
Rendering Primary effluent screenings	DAF float	The inclusion of screenings and DAF or save all scrapings may exclude rendered products from certain markets. Low quality tallow is produced.
Vermicomposting	Manure Paunch contents Aerobic treatment sludges	Worms will readily digest manure and paunch material and the resulting vermicast is claimed to be of high value, but the process requires significant investment and management. Several operations have been successful whereas others have failed.

3.0 Project Objectives

As per the signed agreement, the project will achieve the following objectives to AMPCs reasonable satisfaction:

1. Validate the criteria for paunch stabilization,
2. Determine the application rates for on farm use, and
3. Develop a Beneficial Use Agreement (BUA)/End of Waste (E-of-W) for handling paunch waste (PW).

4.0 Materials and Methods

This work comprised three sets of interconnected experiments, which were conducted under controlled conditions of temperature and soil moisture both in the laboratory and glasshouse. The experiments were: (1) Germination test, (2) Soil incubation study, and (3) Glasshouse study, which are described below. A general characterization of the soil (Table 2) and the range of paunch materials (Table 3) used in the study were also conducted to assist in the interpretation of soil nutrient dynamics and soil × plant interactions. These materials included fresh and composted paunch and will be referred to in the text based on their composting age expressed as number of weeks (from 2 to 16, respectively). Nutrient composition of paunch materials in kg per cubic meter is shown in Appendix 1, based on percentage nutrient composition and (untapped) density values presented in Table 3.

The soil used in the incubation and glasshouse studies was a Black Vertosol, which is common in southern Queensland (Isbell, 2002) and was therefore representative of the area of interest for this work where paunch is likely to be applied.

Table 2: Characterisation of the Black Vertosol used in the laboratory and glasshouse studies. Analyses conducted prior to the experiment to establish baseline levels.

Determination	Unit	Value ± SD	Method
Sand	% (w w^{-1})	9.3±0.58	Bouyoucos (1962)
Clay	% (w w^{-1})	70.6±2.08	
Silt	% (w w^{-1})	20.1±2.00	
Field capacity	% (w w^{-1}) at ⅓ bar	40.4±3.11	Cassel and Nielsen (1986)
Soil bulk density	g cm^{-3}	1.04±0.085	Blake and Hartge (1986)
Soil pH	---	8.55±0.071	Rayment and Lyons (2011)
Electrical conductivity	dS m^{-1}	0.121±0.008	Rayment and Lyons (2011)
Soil organic C	% (w w^{-1})	1.95±0.07	Walkley and Black (1934)
Total N	% (w w^{-1})	0.15±0.01	MAFF (1986, Method No.: 49)
Soil mineral N	mg kg^{-1}	2.4±0.65	MAFF (1986, Method No.: 53)
Extractable P	mg kg^{-1}	20.3±3.89	Colwell (1963)

Table 3: Characterisation of paunch and mineral fertilizers used in the glasshouse study. SD is standard deviation (n=3, except when not shown). Determination of total N and total P are based on MAFF (1986, Method No.: 49), and BS7755 (1998), respectively. SSP is single superphosphate, and number of weeks refers to composting time.

Determination	Total N	Total P	Moisture content	Bulk Density (kg m^{-3})	
Material	(%)	(%)	(%, w w^{-1})	Untapped	Tapped
*2 weeks	1.09±0.07	0.11±0.01	95.6	594±15.1	780±15.6
**4 weeks	0.72±0.00	0.11±0.02	81.6	350±20.6	593±38
**6 weeks	1.41±0.03	0.36±0.07	66.6	379±12.7	530±10.0
*12 weeks	1.89±0.02	0.21±0.01	76.6	176±4.9	249±7.2
**16 weeks	0.96±0.03	0.28±0.02	52.9	407±0.9	490±25.9
Urea	46	---	---	743±6.3****	---
SSP	---	18***	---	1120	---

*Sourced from Site 1, **Sourced from Site 2, ***Total P as P_2O_5 (DEFRA, 2010), ****after Antille et al. (2015a).

4.1 Germination Test

The germination test was conducted to determine the risk of weed contamination or the introduction of non-native species following land application of paunch.

Description of the test

Five types of paunch including fresh, semi-composted and fully composted paunch (Appendix 1) from two Australian abattoir sites were mixed with pure sand using a ratio of 100 g of organic material-to-400 g of oven-dried sand, and paced in plastic containers (dimensions: 200×100×50 mm). Water was subsequently added to the mixture to reach near-saturated conditions (≈90% of saturation), which were maintained throughout the experiment and for a period of three weeks. All treatments including controls (pure sand) were replicated five times and plantule counts conducted daily, and recorded. Figure 1 shows the experimental setup.

Paunch pH and electrical conductivity were measured based on MAFF (1986, Methods No.: 24 (modified), and 33, respectively) to determine if these factors would potentially affect seed germination.

(a) (b)

Figure 1: Overview of the germination test, (a) Treatments: raw, fresh, semi-composted, composted, and control (zero-paunch, not shown), and (b) close-up of a germination tray containing fresh paunch. A description of paunch types is given in Table 3 and Appendix 1, respectively.

4.2 Soil incubation study

The soil incubation study was conducted to determine the nutrient release characteristics from paunch following soil incorporation under controlled laboratory conditions. The study investigated nitrogen (nitrate and ammonium) and extractable phosphorus release patterns over a period of 60 days at constant temperature and soil moisture conditions. Under these experimental conditions, nutrients released to the soil in plant available forms can relate to field conditions using cumulative heat units (Baskerville and Emin, 1969) based on the approach employed by Honeycutt et al. (1988, 1991). From this, likely patterns of nutrients availability in-field conditions can be inferred from studies conducted under laboratory conditions. A limitation of this technique is that it does not account for the effect of wetting-drying cycles (Jedidi et al., 1996). However, it does provide a satisfactory indication of the potential release of nutrients from soil and soil amended with fertiliser materials.

Amendments applied

Nitrogen and phosphorus release characteristics from a six-week composted paunch (Table 3 and Appendix 1) were compared with urea (46% N) and single superphosphate (18% P_2O_5) fertilisers. A control soil (zero-amendment) was also used to quantify the nutrient contribution from soil. All treatments including controls were replicated four times (Kokkora et al., 2008). The paunch and mineral fertilisers were mixed with soil in 0.75 L capacity pots, and placed in an incubator for a period of sixty days (Figure 2). The temperature in the chamber was maintained constant at 25±0.5°C, and soil moisture in the pots was maintained between field capacity (40.4%, w w^{-1}) and 80% of field capacity throughout the experiment.

The approach described above has been satisfactorily used in previous studies investigating nutrient release characteristics from organic materials applied to soil (e.g., Chescheir et al., 1986; Antille et al., 2014a-b).

Description of soil sampling and analyses

Soil mineral nitrogen (SMN) was determined based on MAFF (1986, Method No.: 53) following extraction with KCl, and reported as the sum of nitrate-N (NO_3^--N) plus ammonium-N (NH_4^+-N). Soil extractable phosphorus was determined based on Colwell (1963) by extraction with $NaHCO_3$. Soil sampling was conducted at 0 (baseline level), 3, 7, 15, 30, 45, and 60 days from the start of the incubation period on both control and treatments, respectively.

(a) (b)

Figure 2: Overview of incubation study conducted in the laboratory under controlled conditions of temperature and soil moisture, (a) incubation chamber, and (b) close-up of a pot.

4.3 Glasshouse Study

This study was conducted to determine the agronomic efficiency of paunch applied to a grass crop (*Lolium perenne* L.) grown in pots under controlled environmental conditions in a glasshouse. The agronomic efficiency of the organic materials was assessed by determining: (1) Aboveground biomass referred to in the text as field equivalent dry matter yield (DMY), (2) Nitrogen uptake, and (3) Nitrogen use-efficiency (NUE). This assessment was conducted by comparing five types of paunch with mineral fertilisers of known performance, and controls (zero-amendment), respectively.

Controls were used to quantify soil's nutrients contribution to biomass yield and nitrogen uptake, and to enable NUE from fertiliser- or paunch-treated grass to be estimated using the difference method (Baligar et al., 2001). The glasshouse experiment supplements information derived from the incubation study, and will assist the design of full-scale experimentation as well as the development of preliminary guidelines for land application rates.

Description of the experiment

The experiment used the same materials described for the germination test, which were sourced from two Australian abattoir sites (Table 3, Appendix 1), and it also included a treatment with urea and single superphosphate. Field equivalent application rates were: control (zero-amendment), 150 and 300 kg ha^{-1} of N, respectively. All treatments, including controls were replicated three times. Preparation of pots and mixing of fertiliser materials with soil were based on the approach used by Antille et al. (2014). Dry matter yield (DMY) was determined by hand-cutting the grass to a height of 40 mm, at regular intervals of 25 days after emergence, which was recorded at day 8 after seeding. The time interval for cutting of the grass was consistent with recommendations reported in earlier studies for maximum yield (e.g., Fulkerson et al., 1993; Antille et al., 2015b).

At the time this report was produced, a total of four cuts were completed, however the experiment will be continued to include six cuts. Total fresh weight was determined and a subsample was taken for determination of dry matter, and total N content in plant material, which was determined based on MAFF (1986, Method No.: 48). From this, nitrogen uptake was derived and used to determine NUE, as follows (Equation 1, after Baligar et al., 2001):

$$NUE = \left(\frac{N_F - N_{F=0}}{N_{Rate}} \right) \tag{1}$$

Where: NUE is nitrogen use-efficiency (kg kg^{-1}), N_F and $N_{F=0}$ are N uptakes (kg ha^{-1}) corresponding to fertilizer or organic amendment treatments and control (zero-amendment), respectively, and N_{Rate} is field equivalent N application rate (kg ha^{-1}). Nitrogen content in plant material was determined for the first three cuts only. Pots were placed in a glasshouse facility available at USQ and maintained near-field capacity conditions and at 25±3°C throughout the experiment to enable cross-comparison of experimental data with that derived from incubation studies. The experimental setup in the glasshouse is shown in Figure 3.

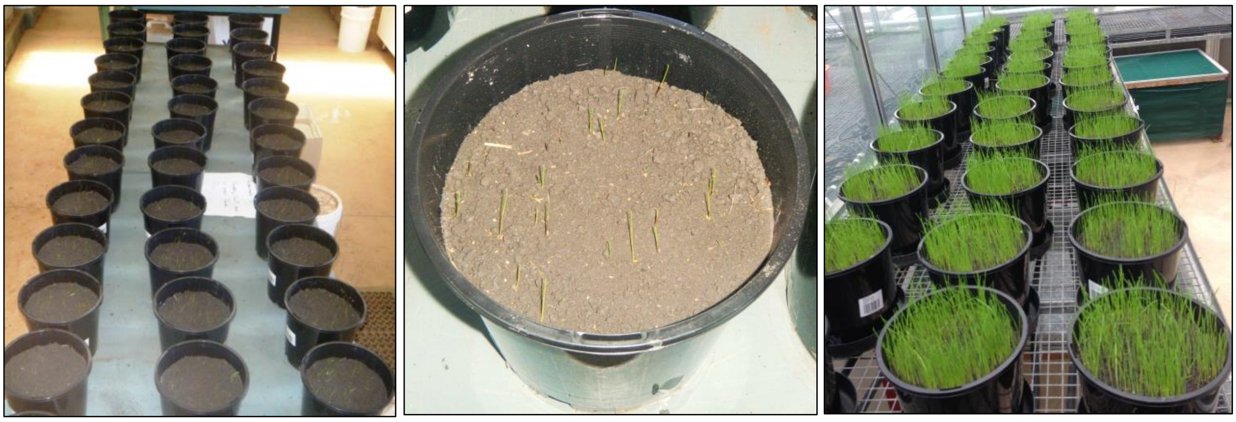

(a) (b) (c)

Figure 3: Overview of the pots experiment conducted in a glasshouse under controlled conditions of temperature and soil moisture, (a) preparation of pots, (b) close-up of a pot (note plants starting to germinate), and (c) established grass in pots seven days after germination.

4.4 Statistical analyses

Statistical analyses were undertaken using GenStat release 16th Edition (VSN International, 2013) and involved analysis of variance (ANOVA), and the least significant differences (LSD) to compare means using a probability level of 5%. Repeated measurement of ANOVA was employed to analyse data derived from the incubation studies, and also to compare measured crop attributes between-cuts, using the same probability level. Dry matter yield-to-nitrogen responses were investigated by means of simple (linear) regression analyses. Quadratic functions were also fitted to the data and results are discussed. The analyses conducted were graphically verified by means of residual plots. Normalization of the data was not required.

5.0 Results

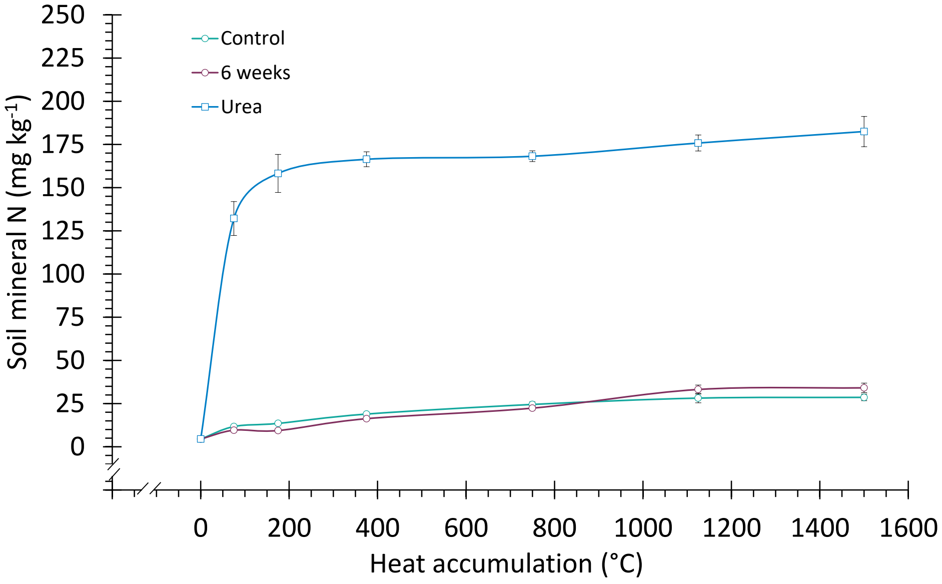
5.1 Germination test

The main results derived from this test are summarised below:

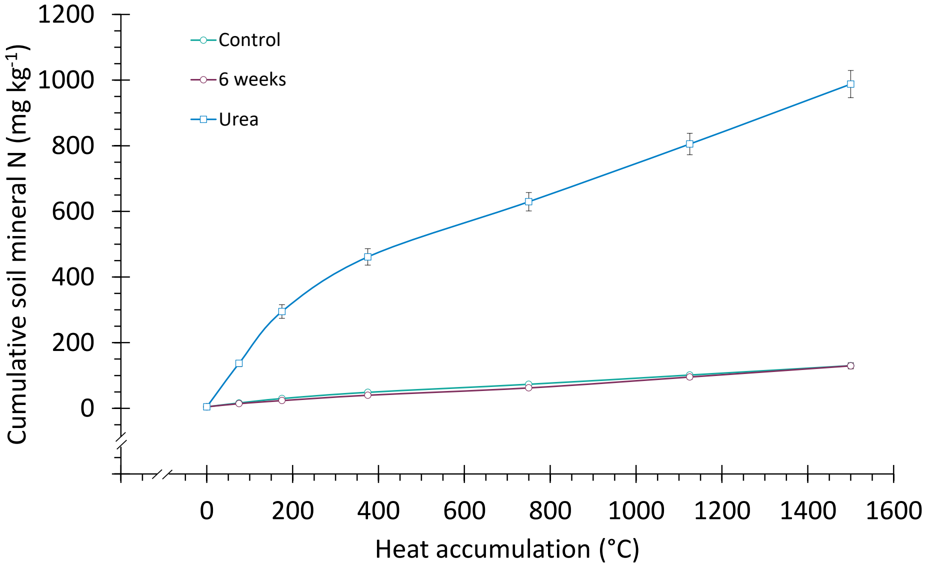
- The number of plantules germinated after three weeks reported a value of zero in all daily observations and treatments. This suggested low (or no) risk of weed contamination in soil amended with paunch whether fresh or at varying degrees of composting,
- However, given weed species often exhibit dormancy (temporary absence of germination capacity) even under satisfactory conditions for germination (Vivian et al., 2008), the risk of weed contamination in soils receiving paunch may not be completely discarded. Therefore, application of alternative methods to determine risk of weed contamination warrants further investigation,
- Given values of paunch pH (range: 7.18-7.87) and EC (range: 0.40-0.69 dS m^{-1}) encountered in paunch samples, there was not sufficient evidence to suggest that seed germination was inhibited by these factors.

5.2 Soil incubation study

The results derived from the laboratory incubation study are shown in Figures 4 and 5 for soil mineral nitrogen (ammonium-N + nitrate-N) and soil extractable phosphorus (Colwell-P), respectively.



(a)



(b)

Figure 4: Mineral nitrogen (ammonium-N + nitrate-N) recorded over the 60-day incubation period in unfertilised control soil, and soil treated with 6-week old composted paunch and urea, respectively. In (a): soil mineral N concentrations as a function of cumulative heat units, and (b): cumulative soil mineral N as a function of cumulative heat units. Error bars denote standard deviation of mean (n=4), P<0.05.

Cumulative soil nitrogen supply from paunch-treated soil, relative to urea-treated soil, was approximately 15% over a 60-day incubation period (≈1500 cumulative degree-days), and was marginally higher than untreated control soil after about 1000 cumulative degree-days. This suggested a nitrogen immobilisation phase followed by a slow-release phase after that time. There was not effect of paunch on soil extractable P, therefore values of Colwell-P remained close to constant over the 60-day incubation period (≈1500 cumulative degree-days). The mineral fertiliser treatment showed significantly higher Colwell-P levels throughout the experiment, which agreed with relates studies (e.g., Antille et al., 2014b).

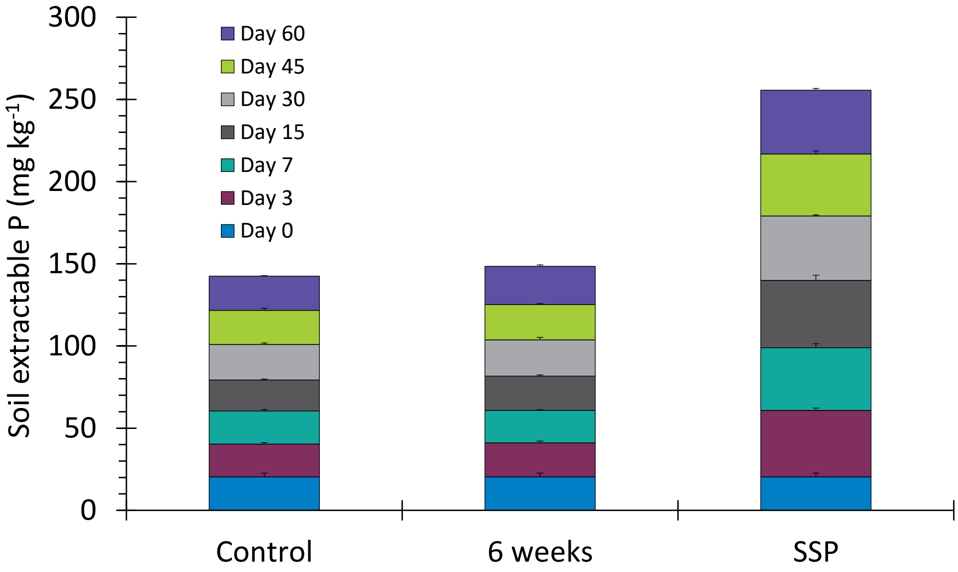


Figure 5: Extractable phosphorus (Colwell-P) recorded over the 60-day incubation period in unfertilised control soil, and soil treated with 6-week old composted paunch and single superphosphate (SSP), respectively. Error bars denote standard deviation of mean (n=4), P>0.05.

5.3 Glasshouse study

5.3.1 Dry matter yield

Dry matter yield (DMY) recorded over four cuts is shown in Figure 6. Overall, there were significant differences in DMY between unfertilised controls and treatments ($P<0.001$). There were also significant effects of amendment type, nitrogen (N) application rate, and interaction amendment × N application rate on DMY (P-values <0.05). The amendment type effect was mainly due to differences in DMY between urea and all types of paunch, particularly at cuts 1 and 2. However, these differences were relatively smaller at cuts 3 and 4, and non-significant except for higher (≈10% on average) DMY level in grass treated with the 6 week-old material compared with other treatments (LSD 5% level: 95.7). DMY recorded in treated grass at cuts 3 and 4 was marginally higher but not statistically different than unfertilised controls (LSD 5% level: 117.2), which suggested low mineral N supply rates from the organic materials. Despite this, less stabilisation of organic matter in raw (<2 week-old) and semi-composted (6 week-old) materials suggested that both C and N fractions were more readily available, and therefore N supply to the plant was affected to lesser extent compared with fully composted paunch.

Figure 6 also shows that overall differences in DMY between-paunch treatments applied at field equivalent rates of 150 and 300 kg ha^{-1} of N were less than 10% on average, which supports the above statement and denotes little agronomic benefit of paunch applied at the higher rate used in this study. For urea, there was a 22% difference in cumulative DMY over four cuts when applied at 150 and 300 kg ha^{-1} of N, respectively.

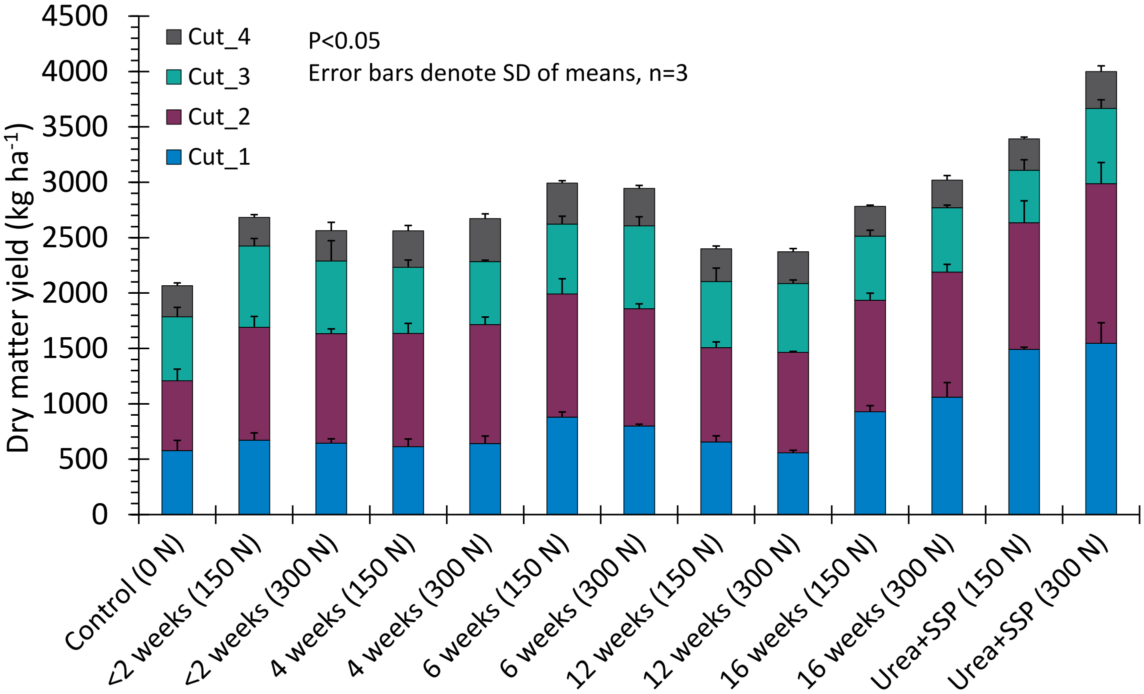


Figure 6: Dry matter yield recorded over four cuts after a single application of mineral fertilisers and paunch to ryegrass. Number of weeks denotes compost age, followed by field equivalent N application rate in kg per ha.

Table 4 shows dry matter yield-to-nitrogen responses encountered after a single application of paunch or fertiliser-N, and over four consecutive cuts. Responses were essentially linear for the range of N application rates investigated (*P*-values <0.05), which agrees with earlier studies dealing with synthetic N sources (e.g., Reid, 1985; Antille et al., 2015b), and organic materials used in ryegrass (e.g., Antille et al., 2014). Despite this, nonlinear responses were also fitted to the data, but estimate of parameters for the square term were not significant (*p*-values >0.05), which was observed for all amendments used in this study. Therefore, DMY-to-N responses were better explained by linear functions, which showed significance to the linear term (*P*-values <0.05). This was expected because of the range of N application rates investigated; however, nonlinear functions may be possible with a more complete dataset (e.g., Sparrow, 1979; Morrison et al., 1980; Antille et al., 2013). Linear regression analyses conducted for each paunch type explained, individually, relatively more variation than it did a common slope ($P<0.05$, R^2 =0.56) because of the amendment × N rate effect (P<0.05), with the exception of the fully composted material from Site 1 (R^2 =0.40). Figure 7 displays distribution of DMY data recorded over four consecutive cuts for control, mineral fertiliser- and paunch-treated grass. Note median value of grass treated with the 6 week-old composted paunch is approximately equivalent to that of the mineral fertiliser treatment.

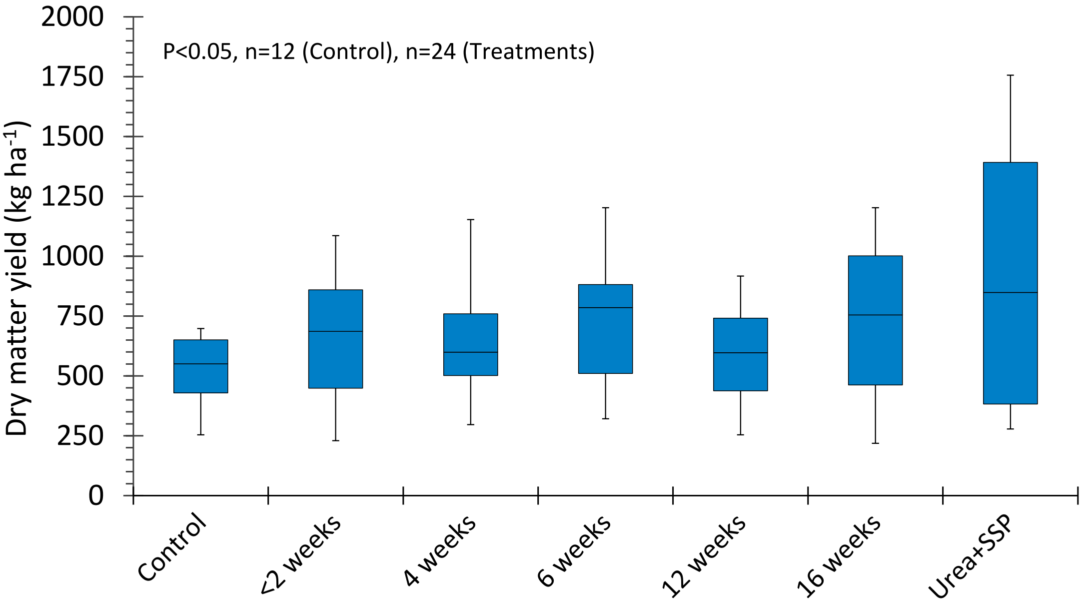


Figure 7: A box-plot comparing the overall agronomic effectiveness of single application of mineral fertilisers and paunch to ryegrass over four consecutive cuts. Box-plots show: Min, Q_1, Med, Q_3, and Max, respectively. Use n=12 (control), n=24 (treatments), number of weeks denotes compost age.

The slopes derived from the set of linear functions presented in Table 4 denote agronomic efficiency of N applied as fertiliser (kg DMY kg^{-1} N). Responses were greater with 6 week- and 16 week-old composts from Site 2 (≈3.1 kg kg^{-1}) compared with other materials, but about 50% lower than that obtained with urea (≈6.5 kg kg^{-1}). Nitrogen responses encountered in this study (range: 1-6.5 kg DMY kg^{-1} N) were generally lower than the range (10-30 kg DMY kg^{-1} N) reported in the literature for synthetic N fertilisers used in ryegrass grown in subtropical environments (e.g., McKenzie, 1996; Callow et al., 2003). However, it is acknowledged the fact that our study comprises only four cuts over less than 100 days, and that it was conducted during the autumn period without accounting for seasonal patterns of grass production, (e.g., Fulkerson et al., 1998; Cullen et al., 2008; Vogeler et al., 2016). Differences in responses observed between mineral fertiliser and organic amendment treatments are also explained by N × P interaction effect on DMY (Mouat and Nes, 1983; Fageria, 2001). As shown in Figure 5, relatively higher availability of single superphosphate-P compared with paunch-P is mentioned as a contributing factor to enhanced uptake and DM partitioning of urea-N compared with the organic material.

Table 4: Dry matter yield-to-nitrogen responses recorded over four cuts after a single application of mineral fertiliser and paunch to ryegrass. Number of weeks denotes compost age.

Material	Response	*P*-value	R^2
2 weeks	$DMY = 2183 + 1.78N$	<0.05	0.51
4 weeks	$DMY = 2131 + 2.02N$	<0.05	0.70
6 weeks	$DMY = 2200 + 3.03N$	<0.05	0.74
12 weeks	$DMY = 2127 + 1.02N$	<0.05	0.40
16 weeks	$DMY = 2147 + 3.18N$	<0.05	0.86
Urea + Single superphosphate	$DMY = 2152 + 6.45N$	<0.001	0.93

5.3.2 Nitrogen in plant material, uptake and use-efficiency

Figure 8 shows distribution of data corresponding to nitrogen in plant material recorded over the first three cuts for control, mineral fertiliser- and paunch-treated grass, respectively. Note the median value of grass treated with 6-week old compost was approximately equivalent to the mineral fertiliser treatment (≈2.6% N). For the mineral fertiliser treatment, a relatively wide range of values (Q_1 =2.1% N, Q_3 =3.6% N) compared to all types of paunch (Q_1: 2.3-2.5% N, Q_3: 2.4-2.7% N) reflects significant effect of nitrogen application rate on total N in plant material ($P<0.05$), which was not observed in paunch-treated grass ($P>0.05$). Low N supply to grass crops compromises growth rate, tiller density and therefore biomass production, and may also reduce N concentration in plant (Wilman et al., 1976; Delagarde et al., 1997). High-producing dairy cows require N contents in grass in the range of 2.2% to 2.7% (Dalaby et al., 1996**;** Peyraud and Astigarraga, 1998). Values of total N in plant material encountered within this study for both paunch and mineral fertilisers were with the range reported in the literature for fertilised ryegrass (e.g., Wilman and Mohamed, 1980; Lowe et al., 1999). However, for paunch-treated grass values within that critical range may be explained by relatively low biomass production (no dilution effect), and the frequency of cutting (Aavola and Kärner, 2008; Reyes et al., 2015).

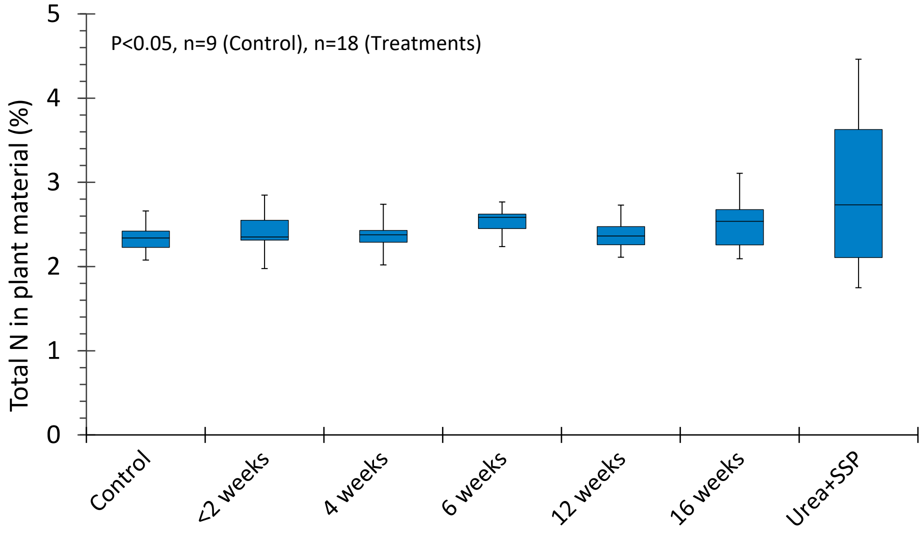
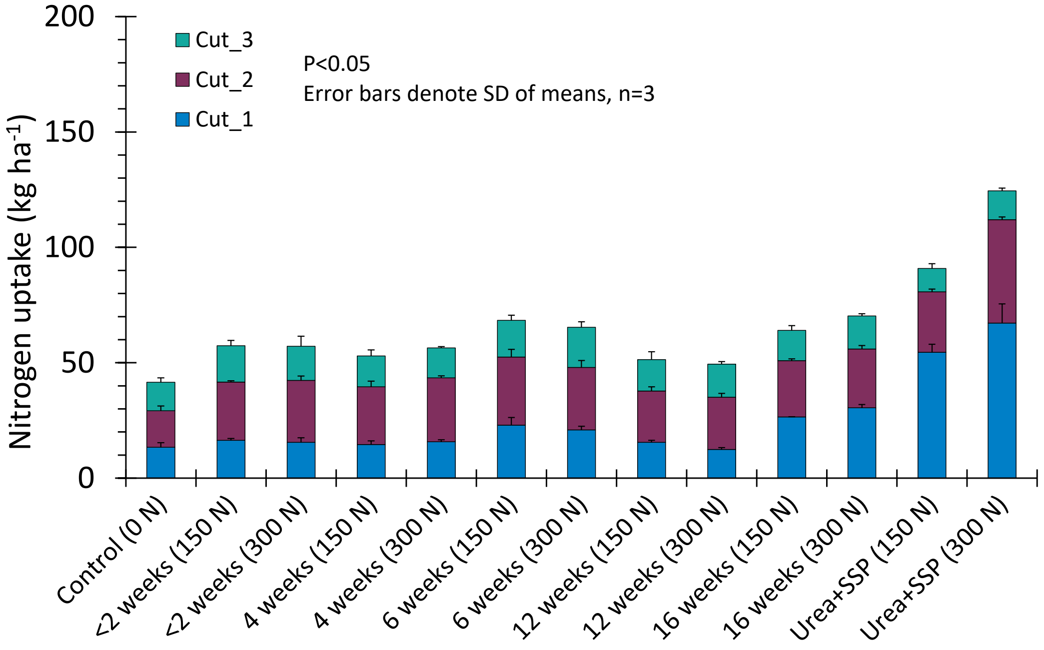


Figure 8: A box-plot comparing total nitrogen content in plant material over three cuts and after a single application of mineral fertilisers and paunch to ryegrass. Box-plots show: Min, Q_1, Med, Q_3, and Max, respectively. Use n=9 (control), n=18 (treatments), number of weeks denotes compost age.

Figure 9 shows nitrogen uptake by grass over the three first cuts. Overall, N uptake was significantly higher ($P<0.05$) in paunch and fertiliser-treated grass compared with controls (by ≈60% on average over the first three cuts). There were also significant amendment type and nitrogen application rate effects on nitrogen uptake, which were observed in all cuts (P-values <0.05). Despite this, the N application rate effect was mainly due to differences (≈35%) in N uptake in the mineral fertiliser treatment applied at 150 and 300 kg per ha of N, respectively. Overall differences in cumulative N uptake between-treatments were in the order: mineral fertiliser > 6 weeks = 16 weeks > 2 weeks = 4 weeks > 12 weeks, respectively.

However, N uptake in cut 3 reduced by approximately 50% across all treatments compared with the first two cuts, and approximated N uptake levels observed in controls (≈13 kg ha^{-1} of N). Higher uptake in 16 week-old compared with 12 week-old composts may be attributed to qualitative differences in carbon (C) fractions (labile *vs*. non-labile) of the organic material affecting nutrient release and therefore plant uptake (Fontaine et al., 2003). These differences in compost C may be due to the actual composting process (note that both materials originated from different sites) as well as the quality of the animal feed influencing C dynamics during the stabilisation process. These observations require further investigation including qualitative assessment of C fractions in composted paunch (e.g., Schnitzer, 1982; Garcia et al., 1991).



P<0.05
Error bars denote SD of means, n=3

Figure 9: Nitrogen uptake recorded over four three cuts and after a single application of mineral fertilisers and paunch to ryegrass. Number of weeks denotes compost age, followed by field equivalent N application rate in kg per ha.

Figure 10 shows nitrogen use efficiency (NUE, Equation 1) derived from cumulative N uptake over the first three cuts. Overall, there were significant effects of treatments and N application rates on NUE. On average, NUE decreased in the order: mineral fertiliser > 6 weeks ≈ 16 weeks > 2 weeks ≈ 4 weeks > 12 weeks, respectively. Values of NUE relative to the mineral fertiliser treatment were approximately 40% in the 6- and 16-week-old composts, but reduced to 25% or less in the other paunch materials. On average across all fertiliser materials, NUE was approximately 50% lower when applied at 300 kg ha^{-1} of N than at 150 kg ha^{-1} of N. As shown in Figure 6, differences in DMY for paunch-treated grass at 150 and 300 kg ha^{-1} of N were small. These results show that there is little agronomic benefit in applying paunch at field equivalent rates higher than 150 kg ha^{-1} of N, and the same is true in terms of grass quality as N content in plant material changed only within a narrow range (Figure 8). From the range of paunch materials used in this study, it appears that the highest agronomic efficiencies are achieved with the 6- and 16-week-old composts applied at 150 kg ha^{-1} of N, respectively. A 6-week composting period has operational as well as financial advantages compared with 16-week period.

Such a practice may therefore be justified, which will also result in higher agronomic performance compared with either shorter or longer composting periods. However, the implications of using relatively less stabilised paunch materials on soil C stock and C dynamics are not well understood and therefore requires investigation, particularly in low C soils (e.g., SOC <1%).

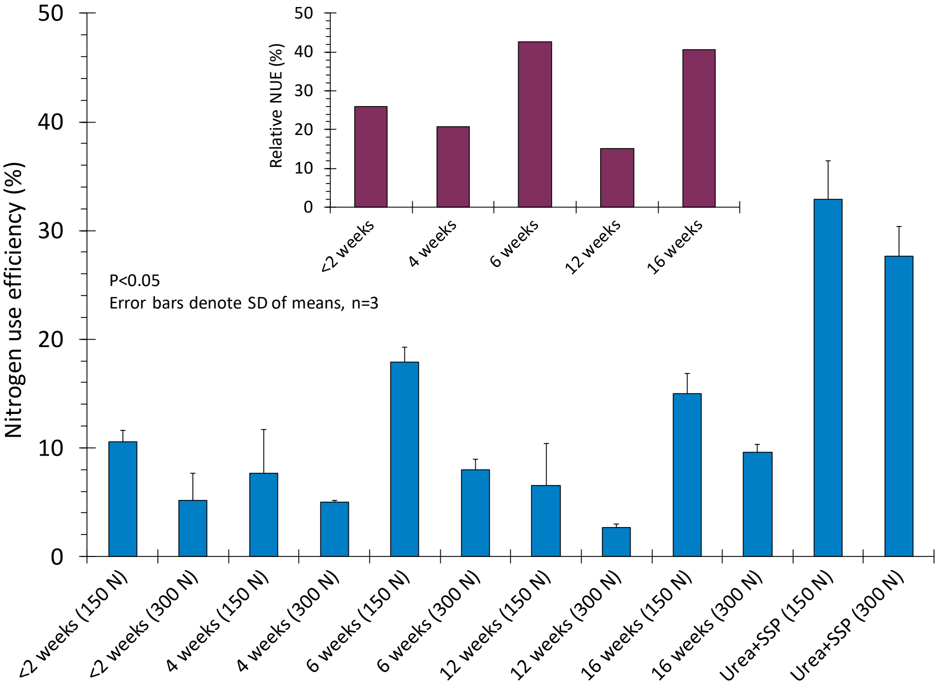


Figure 10: Nitrogen use efficiency (NUE) recorded over three and after a single application of mineral fertilisers and paunch to ryegrass. Number of weeks denotes compost age, followed by field equivalent N application rate in kg per ha. Superimposed figure shows NUE of paunch relative to NUE of mineral fertiliser treatment (averaged NUE over the two N application rates used in this study).

6.0 Discussion

6.1 Criteria for paunch stabilisation

The six week-old compost showed relatively higher agronomic performance compared with all other paunch types. Thus, a six-week stabilisation period may be suggested as reference for paunch, and may be used as guidance until further studies are undertaken. However:

- Criteria for stabilisation of paunch based on carbon maturity levels of the organic material being composted, which may be more appropriate than fixed composting times,
- The above approach may allow for greater consistency in composted paunch used for land application by: (1) capturing seasonal effects of weather on microbial activity and carbon dynamics within compost piles, and (2) accounting for differences in composting techniques and paunch sources (composition) across the industry,

This approach requires identifying suitable analytical techniques for determination of organic carbon fractions in compost with varying degree of stabilisation, including biologically labile, semi-labile and recalcitrant forms of carbon, respectively.

6.2 Pathogen testing

Current Australian guidelines place paunch waste in the guidelines for controlled putrescible and organic waste with the national environment protection movement: of controlled waste between states and territories measure (NEPM) code K100 (Latimer, 2015). The Australian guidelines outlined highlight general issues around organic wastes rather than those specific to paunch but acknowledge pathogen potential. For land application composting guidelines serve as an appropriate proxy for acceptable levels of pathogens. Queensland composting guidelines state: '*…the end product does not contain pathogens or contaminant levels that when applied could cause harm to the environment and human health…*'

The national Australian standard level states that the following methods should be used to determine pathogens (Australian Standards, 2012).

- Joint AS/NZS 4276.7:2007 – Water microbiology – *Escherichia coli* and thermotolerant coliforms – Membrane filtration method. Sydney, NSW, Australia: Council of Standards Australia.
- AS 5013.10 – 2009 Food microbiology – Microbiology of food and animal feeding stuffs- Horizontal method for the detection S*almonella spp.* Sydney, NSW, Australia: Council of Standards Australia.

Methods are supplied in the appendix and state that threshold levels are as follows:

- *Salmonella spp*.: absent in 50 g dry weight equivalent,
- Faecal coliforms < 1000 MPN/g (dry weight equivalent).

Plant pathogens are not tested for due to a lack of validated methods

It is a requirement that testing occurs prior to the distribution of any batch of compost. Each pile in a given batch should be tested. The number of subsamples required from a pile is dependent on the pile size.

Pile volume, m^3	Number of sub-samples required
<575	12

1000	16
2000	23
3000	28
>3600	30

In addition to biological pathogens other contaminants must have acceptable levels to meet Australian standards and to avoid other potential diseases. Further information on contaminants can be found in table 3.3 of Australian Standard, 2012.

6.3 Paunch management and handling

The following points should be taken into account when managing and handling paunch for land application:

- Ensure consistency in terms of chemical composition (nutrients), physical properties (moisture content and density), and degree of stabilisation (carbon maturity levels),
- Reduce moisture content where practical/economical,
- Determine if granulating (or alternatively pelletising) of paunch are technically and economically feasible options. This will allow for:
  - Bagging e.g., 1 ton bags for ease of transport, storage on-farm, preservation of product quality, accurate dosage,
  - Optimisation of particle size range and aerodynamic properties to make it compatible with commercially available fertiliser spreading equipment (e.g., twin-discs spreaders or pneumatic applicators), and improved in-field delivery,
- Current practice for field application appears to be non-sustainable from the soil heath perspective. There is a need to minimise traffic intensity to avoid soil compaction, which may offset potential benefits associated with recycling of paunch to land and lead to secondary effects, namely: (1) increased risk of nitrous oxide emissions, (2) increased risk of nutrient and carbon losses in runoff, and (3) reduced nutrient use-efficiency,
- If granulation of paunch was deemed not feasible, manure type spreaders may be recommended although the delivery mechanism of these machines does not normally allow for high degree of control over the amount of material applied compared with twin discs or pneumatic equipment.

6.4 Criteria for land application

The criteria for land application should consider the 4R principles of nutrient stewardship, namely: right source, right rate, right time, and right place (Roberts, 2007). These principles are shown in Figure 11 (after The Fertilizer Institute, 2016, http://www.nutrientstewardship.com/4rs), and provide a conceptual framework to manage nutrients in an agronomically, economically and environmentally sound manner.

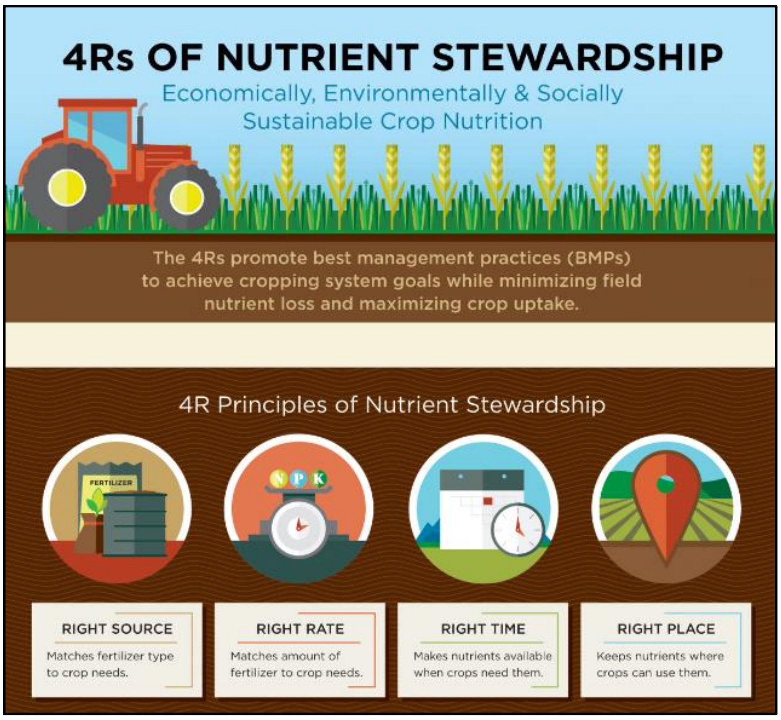


Figure 11: The 4R principles of nutrient stewardship used to exemplify basis for management of nutrients in paunch (after The Fertilizer Institute, 2016, retrieved from: http://www.nutrientstewardship.com/4rs).

Best management practice (BMP) for nutrients in paunch may be developed upon the 4R principles, as discussed here:

- **Right source:** matches paunch type to soil and cropping system. Based on our experimental work under controlled conditions, semi-composted paunch (6 week-old) showed the highest agronomic performance in all measured crop attributes. However, the effectiveness of paunch may vary depending upon specific soil and crop conditions, for which preliminary results reported in this work, may only be taken as guidance until further studies are undertaken. Combined mineral and organic fertilisation whether blended or splits may be a suitable approach to match short- and longer-term (season, rotation) demand for nutrients by crop (e.g., Han et al., 2004).
- **Right rate:** matches amount of paunch to nutrient demand by the crop. Our experimental work suggested no agronomic benefit when paunch-N application rate was increased from 150 to 300 kg per ha (field equivalent). Above that rate, paunch nitrogen use-efficiency decreased significantly. Therefore, a preliminary recommendation is made for land application rates in grass crops not to exceed 150 kg per of paunch-N. This recommendation requires validation under field conditions, and for a wider spectrum of crop and soil types than that used in this study. Routine applications of organic materials with low (e.g., <1) N:P ratio can lead to build-up of soil-P (Sadeghpour et al., 2016), which needs to be observed, particularly in soils with satisfactory P supply,
- **Right time:** matches nutrient availability to nutrient uptake by a growing crop. Based on soil incubation data, it appears that net mineralisation of N from paunch with intermediate level of composting (6 weeks) becomes positive after about 1000 cumulative degree-days (Figure 4a). Therefore, application in early autumn or early spring for establishment of winter and summer crops in the Darling Downs region of Queensland, respectively, may be appropriate.

- **Right place:** refers to application technique (method and placement) so that utilisation of paunch nutrients by the crop can be maximised. Our experimental work simulated soil incorporation of paunch for establishment of grass crops. Further work is required to determine the efficiency and environmental implications of surface-applied paunch in situations where soil incorporation may not be practicable e.g., zero-tillage systems and established grassland (Maguire et al., 2011). Earlier work dealing with application techniques for organic materials is quoted herein, which may assist in developing suitable methods for land application of paunch (e.g., Dosch and Gutser, 1995; Pullen et al., 2004; Laguë et al., 2005, 2006; Landry et al., 2011; Way et al., 2013). Soil incorporation of organic materials often results in reduced emissions compared to surface application (Moseley et al., 1998; Smith and Mukhtar, 2015).

Further requirements for land application

- Where practicable, relatively low paunch-N application rates (e.g., <150 kg ha^{-1} of N) and split applications may be preferred. This approach will likely reduce opportunities for environmental losses of nutrients (avoidance of nutrient flushes derived from mineralisation of organic matter in paunch), particularly N and P in plant available forms,
- Care must be exercised to ensure that field application is not performed in soft soil conditions as traffic compaction will: (1) Significantly reduce use-efficiency of nutrients in paunch, (2) Likely result in additional secondary processes (e.g., increased runoff) that compound the impact and lead to soil sustainability concerns, and (3) Increase costs of ameliorative tillage (Soane and van Ouwerkerk, 1995).

6.5 Fertiliser replacement value of paunch

Nitrogen fertiliser replacement value (NFRP) of paunch was estimated based on the approach reported in Lalor et al. (2011) for cattle slurry, which uses the DMY-to-fertiliser nitrogen response curve to derive NFRV (Equation 2):

$$NFRV = \left(\frac{F_{N(equivalent)}}{Paunch_{N(applied)}} \right) \times 100 \tag{2}$$

Where: *NFRV* is nitrogen (N) fertiliser replacement value of paunch (%, kg kg^{-1}), $F_{N\text{-}(equivalent)}$ is fertiliser N required for equivalent DMY (kg ha^{-1}), and $Paunch_{N\text{-}(applied)}$ is paunch N application rate (kg ha^{-1}), respectively.

Base on the above approach, mean NFRV of paunch applied to grass were 39±19.8% (2 weeks), 35±15.5% (4 weeks), 56±19.3% (6 weeks), 19±17.5% (12 weeks), and 52±13.6% (16 weeks), respectively. Value range of NFRV of paunch within this study was generally higher than those reported in the literature for organic materials applied to grass under field conditions; for example, farm yard manure (range: 37-50%, Pikula et al., 2016), cattle slurry (range: 10-39%, Lalor et al., 2011), and composted household waste (<10%, Petersen, 2003). Field-scale studies are required to validate these preliminary results obtained under controlled conditions in the glasshouse, and determine how timing and method of application (e.g., soil incorporated or surface-applied) influence NFRV of paunch. Based on related studies (e.g., Misselbrook et al., 1996; Laws et al., 2002; Lalor et al., 2014) this is mentioned as an important practical consideration for optimising nutrient recovery in crop and minimising nitrogen losses.

7.0 Conclusions

The main conclusions derived from this work are summarised below:

1. Germination risk:
    a. Risk of weed contamination from soil application of paunch appears to be low. Methods that enable accounting for dormancy of weed seeds, and (viable) seed count may be required to fully discard such a risk.
2. Agronomic performance:
    a. Soil application of paunch increased dry matter yield of ryegrass by 30% on average compared with unfertilised grass, but was approximately 35% lower than the mineral fertiliser treatment,
    b. Dry matter yield-to-nitrogen responses were linear within the N application rates investigated, which was observed with all amendments. Responses varied from 1.1 to 3.2 kg DM kg^{-1} N for paunch-, and about 6.5 kg DM kg^{-1} N for urea-treated grass, respectively,
    c. Nitrogen use-efficiency (NUE) in paunch was approximately 10% on average (range: 3%-20%), and between 0.15 and $0.40 \times NUE_{UREA}$ depending upon paunch type and rate,
    d. The nitrogen fertiliser replacement value of paunch, relative to urea-N, reported an average value of 40±17.1% (single application over three cuts),
    e. The quality of harvested plant material in paunch-treated grass was satisfactory (total N_{PLANT} ranged from 2% to 3%) based on reported nutritional requirements for high-producing cattle.
3. Nutrient release characteristics:
    a. Cumulative soil nitrogen supply from paunch-treated soil, relative to urea-treated soil, was approximately 15% over a 60-day incubation period (≈1500 cumulative degree-days), and was marginally higher than untreated control soil after about 1000 cumulative degree-days. This suggested a nitrogen immobilisation phase followed by a slow-release phase, which needs to be considered when timing land application of paunch. From this, it was suggested that early autumn or early spring applications for establishment of winter or summer crops, respectively, may be appropriate so that nutrient supply and crop demand could be matched. This recommendation may be used to inform the design of field-scale trials that may enable validation of these preliminary findings,
    b. There was not effect of paunch on soil extractable phosphorus (Colwell-P), and values remained close to constant over the 60-day incubation period (≈1500 cumulative degree-days),
    c. Potential risk of build-up of soil phosphorus needs to be assessed over multiple years given apparently low rates of release, and to be able to capture the effect of crop rotation on soil P off-take in grain or biomass.
4. Land application rates and paunch types:
    a. The agronomic performance of paunch applied to grass was similar for the two rates investigated (150 and 300 kg ha^{-1} of paunch-N). Thus, a preliminary recommendation for land application may be made not to exceed the lower rate used in this study, and to supply the balance required by the crop with a straight (mineral) nitrogen source,
    b. Application prior to crop establishment and followed by soil incorporation may be the preferred practice to minimise nitrogen losses and allow for breakdown of organic matter. Soil nitrogen tests using standard techniques, prior to crop establishment, are also recommended to assist decision-making about requirements for nitrogen fertilisation.

8.0 Future research and development requirements

The following areas have been identified as knowledge gaps and therefore merit a research priority. This work is required to further inform soil-, climate- and crop-specific land application rates, optimise agronomic performance and minimise environmental concerns:

1. The criteria for stabilisation of paunch during the composting process based on carbon maturity levels of the organic material may be more appropriate than an approach based on fixed composting time. This will allow for greater consistency in composted paunch used for land application by capturing seasonal effects of weather on microbial activity and carbon dynamics within compost piles, as well as differences in composting techniques and paunch sources across the industry,
2. To determine the effect of paunch on soil carbon dynamics and carbon sequestration in soil, and associated effects on nutrient dynamics, particularly nitrogen, including laboratory and medium- to long-term field studies, and modelling approaches that capture such effects on soil responses and crop productivity,
3. To investigate the effect of paunch on greenhouse gas emissions, including surface application (likely grass based and arable cropping systems under zero-tillage) and shallow incorporation (conventional and minimum tillage cropping systems), respectively,
4. To determine the optimum timing of application for both grassland and arable cropping systems to maximise nutrient recovery in crop biomass and yield, and the optimum number of splits within a calendar year or growing season,
5. To investigate the logistics, and agronomic and economic implications of applying paunch to supply a proportion of the nutrient demand by the crop and the balance with a mineral fertiliser source whether as a blended material (balanced organo-mineral fertiliser) or in split applications. This is based on the fact that paunch will likely provide a relatively low, although sustained, supply of nutrients to crop (slow release source) and possibly over the rotation, whereas the mineral fraction will provide a shorter-term supply of nutrients. This needs to be determined in conjunction with Recommendation (3): Optimum timing for field application,
6. There is a requirement to improve the physical quality of paunch (consistency, particle size, size distribution, density properties, and moisture content) to enable field application with standard fertiliser spreading equipment. For this, a recommendation is made to investigate the feasibility of granulating or pelletising paunch as well as the energy requirements for drying of the organic material. Where feasible, granulation would be the preferred option due to aerodynamic properties, and greater control over the particle size range required for efficient field spreading, reduced segregation and breaking of particles. Compared with current practice for field application such a development will:
    a. Allow for improved field operating efficiency and reduced costs of field application, including labour,
    b. Allow for improved distribution uniformity, and therefore improved nutrient use-efficiency by the crop and reduced risk of nutrient losses to the environment,
    c. Improve logistics both at farm and field levels. Bagging of granulated (or pelletised) paunch will significantly improve handling, storage, facilitate dosage for field spreading. A drier material in the form of granules or pellets will reduce cost of transport and may enable expansion of current land-bank available for recycling (Spence et al., *In preparation*),
    d. The above should also consider mechanisation requirements for field spreading (equipment, settings, and techniques), including adjustments needed to mitigate traffic impacts on soil (e.g., Douglas et al., 1992; Bédard et al., 1997), and soil compaction-related greenhouse gas emissions (Bhandral et al., 2007),
7. There is also a requirement for field validation of the findings derived from the laboratory and glasshouse studies undertaken within this work, which needs to be continued in order to acquire a more complete dataset than that presented in this report,
8. There is a need to perform detailed economic analyses assessed against alternative options available for disposal of paunch, and conduct contingent valuation studies to determine farmers' willingness to pay for enhanced quality paunch-derived materials. Such analyses should be

undertaken as a cost reduction (avoidance) strategy, and may require the final product to be partially subsidised to encourage uptake by farmers,

9. This study focused on primarily on grass response to paunch, and soil nitrogen and phosphorus dynamics. Therefore, further work is required to understand soil dynamics and crop effects of secondary nutrients, including potassium, calcium and magnesium. This is an important practical consideration given paunch-to-fly ash ratios (≈7:1 by weight) typically used in the process,
10. The nitrogen fertiliser replacement value (NFRV) of paunch reported in this study has been derived from (short-term) glasshouse experiment using pots, and therefore requires validation in longer-term trials under field conditions. A similar approach to that employed for paunch nitrogen may be applied to provide estimates of phosphorus fertiliser replacement value of paunch.

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Appendix 1

Table 5: Approximate nutrient composition per cubic meter of paunch, based on values presented in Table 3. Number of weeks denotes compost age.

Material	Origin	Total N (kg m^{-3})	Total P (kg m^{-3})
2 weeks	Site 1	6	0.7
4 weeks	Site 2	3	0.4
6 weeks	Site 2	5	1.4
12 weeks	Site 1	3	0.4
16 weeks	Site 2	4	1.1