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An investigation into the fertilizer potential of slaughterhouse cattle paunch

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Abstract. *In Australia, the red meat processing industry actively seeks approaches to improve the management of solid waste from processing operations and enhance the environmental performance. Recycling of paunch waste to farmland could be a cost-effective and practicable environmental option. However, little is known about the agronomic value of fresh and composted paunch, and the associated requirements for land application. Therefore, a short-term experimental work was undertaken to assess potential risks due to weed seed contamination and determine the agronomic response of ryegrass (Lolium perenne L.) to soil incorporation of paunch. The risk of weed contamination from soil application of paunch appeared to be low; however, methods that account for viability of seeds may be required to fully discard such a risk. Soil application of paunch at field equivalent rates of 150-300 kg ha^{-1} of N increased dry matter yield by ≈30% on average compared with untreated grass, but was approximately 35% lower than a mineral fertilizer treatment applied at the same rates. Dry matter yield of paunch-treated grass was between 2000 and 3000 kg per ha over four consecutive cuts at 25-day intervals. Nitrogen use-efficiency of paunch was approximately 10% (range: 3% to 20%, depending on paunch type), and total N in harvested plant material showed values, which were between 2% and 3%. Overall, there appears to be potential for paunch-derived products to be used as a source of carbon and nutrients in crop production. Areas that merit a research priority within this space are also outlined in this paper. Such work is required to inform soil-, climate- and crop-specific land application rates, optimize agronomic performance, and minimize environmental concerns. There is also a requirement for the value proposition to industry to be determined, including reduced cost of disposal of material via gate fees and fertilizer replacement value.*

Keywords. *Byproducts, Dry matter yield, Compost, Fertilizer replacement value, Nutrient recovery, Nutrient use-efficiency, Recycling of organic waste, Vertisol.*

Introduction

Australia produced approximately 2.6 million tonnes of red meat in 2015 (≈5% of global production) and is the seventh largest beef producer in the world (FAO, 2015). This production results in a significant amount of waste, which requires careful management and disposal to minimize environmental problems, social inconvenience and economic cost (Jayathilakan, et al., 2012; Petrovic, et al., 2015). A large proportion of the waste generated by the red meat industry is produced during slaughter (Arvanitoyannis and Ladas, 2008). Paunch waste is the partially digested feed from the rumen of cattle that is removed during the processing of carcasses, and is a significant contributor to the waste stream of Australian abattoirs (Australian Bureau of Statistics, 2016). For example, a medium-sized abattoir in Australia produces between 60 and 90 m^3 of paunch per week, which equates to about 800 tonnes of paunch (dry matter basis) per year (Spence, 2012). Current disposal methods incur significant costs to abattoirs and are increasingly regarded as non-environmentally friendly options. By contrast, land application of paunch is relatively less expensive compared with traditional disposal methods, and similar to other organic materials, is considered to be the best practicable environmental option in most circumstances, as it supports the waste management hierarchy (Liu and Haynes, 2013; Ksheem et al., 2015; Six et al., 2016). Abattoirs currently undertake one of several options to manage paunch waste, including: (*a*) removal of paunch and other solids off-site, (*b*) composting material on-site and use on-site, and (*c*) composting material on-site and use off-site. For house-locked abattoirs, where land space is not available, composting or processing of paunch cannot be performed on-site. In these situations, paunch is removed off-site to a licensed premise, which incurs significant costs in gate fees and transport. Paunch is subsequently mixed with other bulking agents and sold as either bulk soil conditioner or bagged compost. Consequently, the benefits of the nutrient-rich material are lost to the farming community because the end use is primarily for domestic gardens.

At present, there are no guidelines or industry standards available regarding best management practice of paunch, which poses the challenge of how to recycle this material for beneficial use on farms at an affordable cost to the industry. Abattoirs in southern Queensland (Australia) have proposed one option, which includes firstly holding the paunch and other yard solids on-site for 1-2 weeks, and subsequently transporting the material to a suitable property for up to 3 months before it is used as a soil amendment. Beneficial Use Agreements (BUA) have been developed; however, further work to qualify particulars surrounding the requirements of paunch management and handling is required as well as to determine whether there is sufficient information to satisfy the conditions of BUA for handling of paunch. Furthermore, there is a need for fundamental work to be undertaken on the following key issues: (*a*) validating the criteria for paunch stabilization, and (*b*) determine application rates for on-farm use. There appears to be a paucity of information available in the scientific literature on the beneficial use of paunch as a fertilizer material (e.g., Hansen, 1992). Little is also known about the agronomic efficiency of paunch applied to soil in various degrees of decomposition, from fresh through to fully composted (Wilson, 1992; Fleming and MacAlpine, 2004).

This study aims to determine optimal agronomic and environmentally-safe land application rates to assist the development of best management practices for the use of paunch as a fertilizer in crop production. Such work is required to maximize nutrient recovery in crop biomass and minimize environmental concerns. This preliminary work forms the basis of a broader scope of research which will establish criteria for measuring the stability of paunch, assess potential risks from on-site storage and on- or off-site farm use due to the risk of pathogens and weed seeds contamination and will quantify greenhouse gas emissions (N_2O, CH_4, CO_2) following soil incorporation. The work reported in this paper summarizes preliminary findings derived from a short-term experimental study, which was conducted to: (1) assess potential risks due to weed seed contamination, and (2) determine the agronomic response of ryegrass to soil incorporation of paunch. Two sets of experiments were established under controlled environmental conditions as discussed here, and included laboratory and glasshouse studies, respectively.

Materials and Methods

Two experiments were conducted under controlled conditions of temperature and soil moisture in the laboratory and glasshouse, which included a germination test and a pot trial. A characterization of the soil used in the pot experiment (Table 1) and the range of paunch materials (Table 2) used in the study were also conducted to assist the interpretation of soil nutrient dynamics and soil × plant interactions. These materials included fresh and composted paunch at various degrees of stabilization. Composted paunch is referred to in the text based on its composting age, which is given in weeks (from 2 to 16, respectively). The soil used in the pot experiment was a Black Vertosol, which is common in southern Queensland (Australia) (Isbell, 2002), and was therefore representative of the area of interest for this work where paunch is likely to be applied.

Table 1: Characterisation of the Black Vertosol used in the glasshouse study. Description of analyses conducted prior to the experiment to establish baseline levels. SD is standard deviation, n=3.

Determination	Value ± SD	Unit	Method
Sand (>20 μm)	9.3±0.58	% (w w^{-1})	Bouyoucos (1962)
Silt (2-20 μm)	20.1±2.00	% (w w^{-1})	
Clay (<2 μm)	70.6±2.08	% (w w^{-1})	
Field capacity	40.4±3.11	% (w w^{-1}) at ⅓ bar	Cassel and Nielsen (1986)
Soil bulk density	1040±85	kg m^{-3}	Blake and Hartge (1986)
Soil pH	8.55±0.071	---	Rayment and Lyons (2011)
Electrical conductivity	0.121±0.008	dS m^{-1}	Rayment and Lyons (2011)
Soil organic C	1.95±0.07	% (w w^{-1})	Walkley and Black (1934)
Total N in soil	0.15±0.01	% (w w^{-1})	MAFF (1986, Method No.: 49)
Soil mineral N	2.4±0.65	mg kg^{-1}	MAFF (1986, Method No.: 53)
Soil extractable P	20.3±3.89	mg kg^{-1}	Colwell (1963)

Table 2: 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±37.9
6 weeks	1.41±0.03	0.36±0.07	66.6	379±12.7	530±10.1
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	---

*Total P as P_2O_5 (DEFRA, 2010), ** after Antille et al. (2015a).

Germination Test

The germination test was conducted to assess the risk of weed contamination and the likely introduction of weed species following soil incorporation of paunch. The five types of paunch described in Table 2 (from fresh through to fully composted) were mixed with pure sand using a ratio of 100 g (moist-basis) of organic material-to-400 g of oven-dried sand, and placed in plastic containers (dimensions: 200×100×50 mm). Water was subsequently added to the mixture to reach near-saturated conditions (≈90% of saturation) and was maintained throughout the experiment for a period of three weeks. All treatments including controls (pure sand with no addition of paunch) were replicated five times and plantule counts recorded daily. Figure 1 shows the experimental setup. Paunch pH and electrical conductivity were measured based on MAFF (1986, Methods No.: 24 and 33, respectively) to determine potential effects of these two factors on seed germination.

(a) **(b)**

Figure 1: Overview of the germination test, (a) paunch treatments from 2 to 16 week-old composts, and (b) close-up of a germination tray containing fresh paunch (2 week-old compost).

Glasshouse Study

The glasshouse study was conducted to determine the agronomic efficiency of paunch applied to a ryegrass (*Lolium perenne* L.) grown in pots under controlled environmental conditions of temperature and soil moisture. 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) per ha, (2) nitrogen uptake, and (3) nitrogen use-efficiency (NUE). This assessment was conducted by comparing five types of paunch with mineral fertilizers of known performance, and controls (zero-amendment), respectively. Controls were used to quantify the soil's residual nutrient contribution to biomass yield and nitrogen uptake, and to enable NUE from fertilizer- and paunch-treated grass to be estimated using the difference method (Baligar et al., 2001). The glasshouse experiment will inform the design of future full-scale field experimentation and the development of preliminary guidelines for land application rates.

The experiment used the same materials described for the germination test, which were sourced from local abattoirs in southern Queensland (Australia (Table 1). The experiment included treatment based on urea (46% N) and single superphosphate (0:18:0) to evaluate N application rates. Field equivalent application rates included control (zero-amendment), 150 and 300 kg ha^{-1} of N, respectively. All treatments, including controls were replicated three times (n=3). Preparation of pots and mixing of fertilizer materials with soil were based on the approach used by Antille et al. (2014a). 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 continue to include a total of 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}). Data for N content in plant material was available for the first three cuts only. Pots were placed in a glasshouse facility available at USQ and maintained near-field capacity conditions at 25±3°C throughout the experiment. 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 germination of plants), and (c) established grass in pots eight days after germination.

Fertilizer Replacement Value of Paunch

Nitrogen fertilizer replacement value (NFRP) of paunch was estimated based on the approach reported in Lalor et al. (2011) for cattle slurry, which uses the dry matter yield-to-fertilizer nitrogen response curve to derive NFRV.

Statistical Analyses

Statistical analyses were undertaken using GenStat release 16th Edition (VSN, 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 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.

Results and Discussion

Germination Test

The main results derived from this test are summarized 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 (e.g., Grabe, 1970; Tekrony, 1983; Tompkins et al., 1998) to determine risk of weed contamination warrants further investigation,
- Given values of paunch pH (range: 7.18 to 7.87) and EC (range: 0.40 to 0.69 dS m^{-1}) encountered in paunch samples, there was not sufficient evidence to suggest that weed seed germination was inhibited by these factors. No seeds germination may be attributed to the temperature range developed within the composting paunch windrow (≈50-60°C), which may have reduced seeds' viability as mentioned in related studies (Eghball and Lesoing, 2000).

Glasshouse Study

Dry matter yield (DMY) recorded over four cuts is shown in Figure 4. Overall, there were significant differences in DMY between treated and non-treated grass ($P<0.001$). There were also significant differences between 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%)

DMY in grass treated with the 6 week-old material compared with other treatments (LSD 5% level: 95.7). Dry matter yield recorded in treated grass at cuts 3 and 4 was marginally higher but not statistically different than controls (LSD 5% level: 117.2), which suggested low mineral N supply rates from the organic materials. Despite this, less stabilization of organic matter in fresh (<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 4 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.

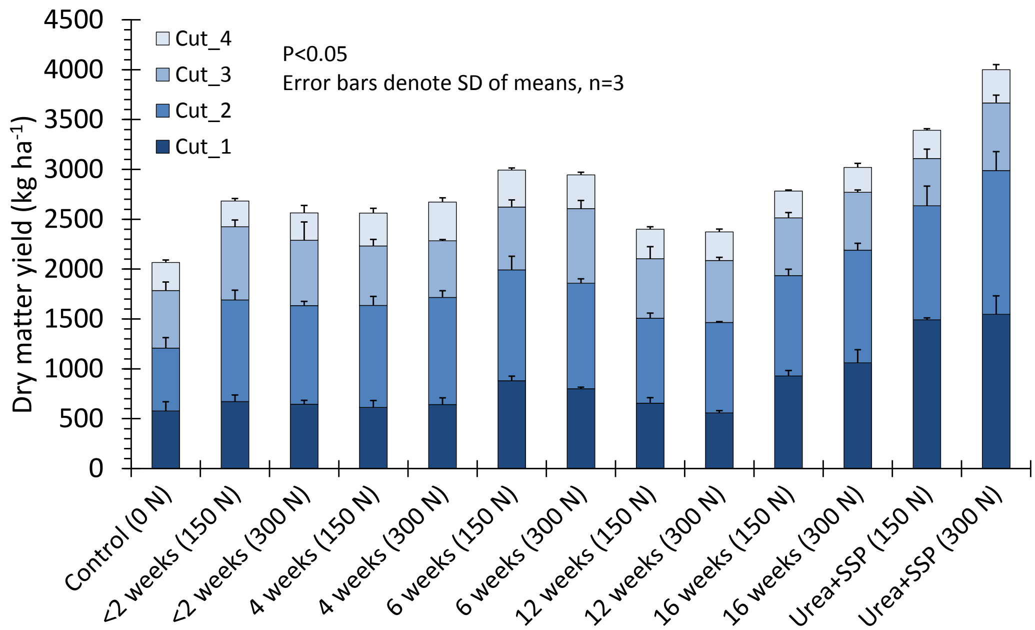

Figure 4: Dry matter yield recorded over four consecutive cuts at 25-day intervals, and after a single application of mineral fertilizers and paunch to ryegrass. Number of weeks denotes compost age, followed by field equivalent N application rate in kg per ha. SD is standard deviation, SSP is single superphosphate.

Table 3 shows dry matter yield-to-nitrogen responses observed after a single application of paunch or mineral fertilizer, 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., 2014a). 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, dry matter yield-to-nitrogen 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., 2013a-b). 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 moderately-composted material (12 week-old), which was sourced from a different abattoir (R^2 =0.40). This observation suggested significant differences in the quality of the paunch material, linked to the composting process (time and pile management), and the type of cattle feed (e.g., grain- or grass-fed or both). The slopes derived from the set of linear functions presented in Table 3 denote the agronomic efficiency of N applied as fertilizer (kg DMY kg^{-1} N). Responses were higher with 6 week- and 16 week-old composts (≈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: 1.0-6.5 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 fertilizers applied to ryegrass grown in subtropical environments (e.g., McKenzie, 1996; Callow et al., 2003). However, it is acknowledged the fact that our study comprised only four cuts over a period of 100 days, and that it was conducted during the autumn without accounting for seasonal patterns of grass growth (Fulkerson et al., 1998; Cullen et al., 2008; Vogeler et al., 2016).

Differences in responses observed between mineral fertilizer and organic amendment treatments are also explained by N × P effect on DMY (Mouat and Nes, 1983; Fageria, 2001). As shown in Figure 5, relatively higher availability of single superphosphate-P (Charleston, 1984) compared with paunch-P is mentioned as a contributing factor to enhanced N uptake and DM partitioning of urea-N compared with the organic material.

Table 3: Dry matter yield-to-nitrogen responses recorded over four cuts after a single application of mineral fertilizer 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	$DMY = 2127 + 1.02N$	<0.10	0.40
16 weeks	$DMY = 2147 + 3.18N$	<0.05	0.86
Urea + single superphosphate	$DMY = 2152 + 6.45N$	<0.001	0.93

Nitrogen in plant material, uptake and use-efficiency

Figure 5 shows distribution of data corresponding to N in plant material recorded over the first three cuts for control, mineral fertilizer- and paunch-treated grass, respectively. Note the median value of grass treated with the 6-week old compost was approximately equivalent to that of the mineral fertilizer treatment (≈2.6% N). For the mineral fertilizer 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). For example, high-producing dairy cows require N contents in grass in the range of 2.2% to 2.7% to sustain satisfactory production levels and milk quality (Delaby et al., 1996; Peyraud and Astigarraga, 1998). Values of total N in plant material encountered within this study for both paunch and mineral fertilizers were within the range reported in the literature for ryegrass fertilized with synthetic N sources (e.g., Wilman and Mohamed, 1980; Lowe et al., 1999). For paunch-treated grass values within that critical range of N contents may be explained by relatively low biomass production (no dilution effect), and the frequency of cutting (Aavola and Kärner, 2008; Reyes et al., 2015).

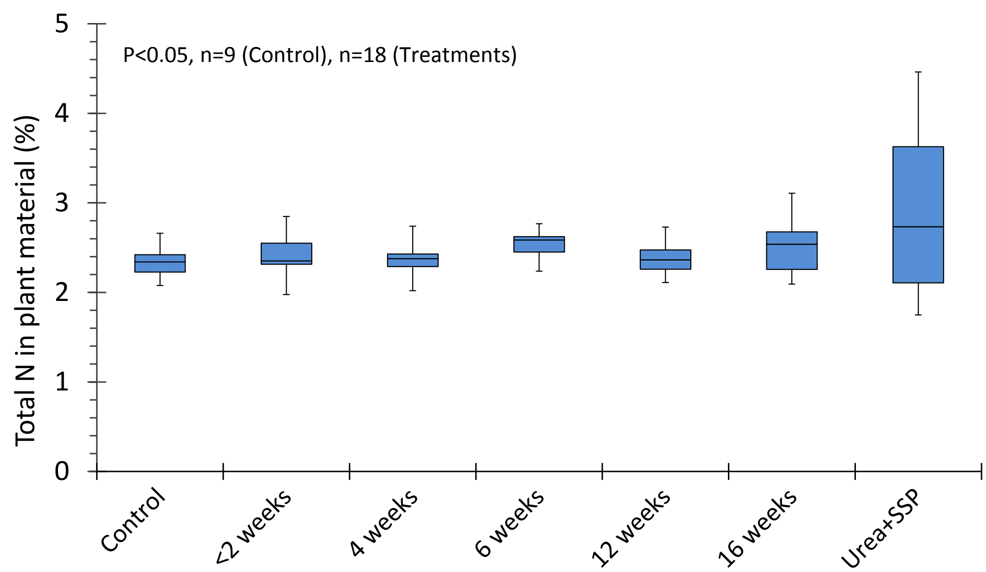

Figure 5: A box-plot comparing total nitrogen content in plant material over three consecutive cuts at 25-day intervals, and after a single application of mineral fertilizers and paunch to ryegrass. Box-plots show: Min, Q_1, Med, Q_3, and Max, respectively. Use n=9 (control), n=18 (treatments), number of weeks denotes compost age. SSP is single superphosphate.

Figure 6 shows nitrogen uptake by grass over three consecutive cuts. Overall, N uptake was significantly higher ($P<0.05$) in paunch and fertilizer-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 fertilizer 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 fertilizer >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; Culman et al., 2013; Antille et al., 2014b). These differences in compost-C may be due to the actual composting process (note that the 12 and 16 week-old composts were sourced from different abattoirs) as well as the quality of the animal feed influencing C dynamics during the stabilization process. These observations require further investigation including qualitative assessment of C fractions in composted paunch (e.g., Schnitzer, 1982; Garcia et al., 1991; Lucas and Weil, 2012).

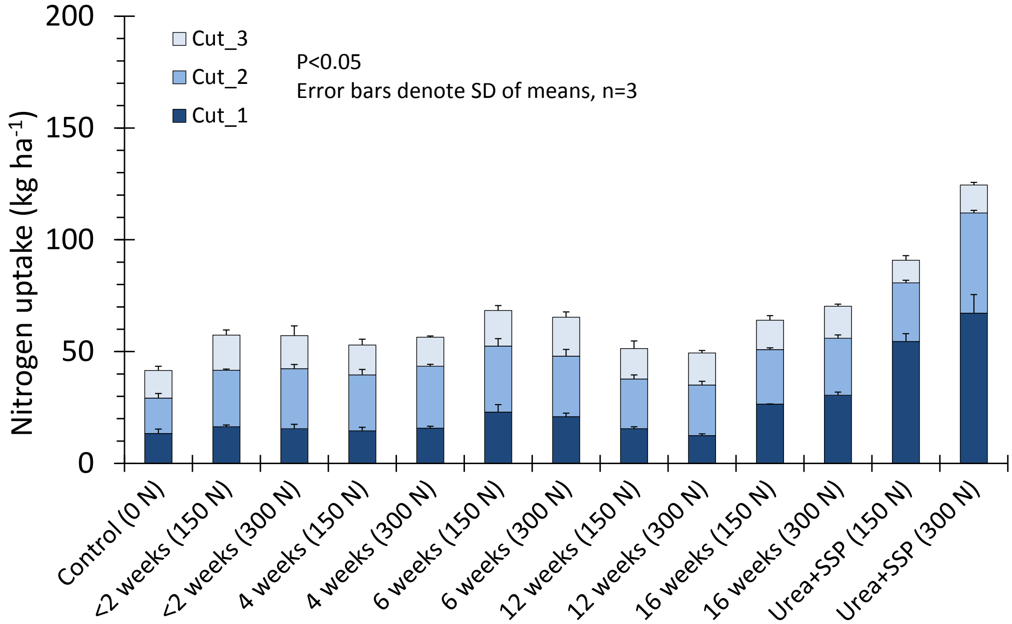

Figure 6: Nitrogen uptake recorded over three consecutive cuts at 25-day intervals, and after a single application of mineral fertilizers and paunch to ryegrass. Number of weeks denotes compost age, followed by N application rate in kg per ha (field equivalent rate). SSP is single superphosphate.

Figure 7 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 fertilizer >6 weeks ≈ 16 weeks >2 weeks ≈ 4 weeks >12 weeks, respectively. Values of NUE relative to the mineral fertilizer treatment were approximately 40% in the 6 and 16 week-old composts, but reduced to 25% or less in all other paunch materials. On average across all type of amendments, 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 4, differences in DMY for paunch-treated grass at 150 and 300 kg ha^{-1} of N were small. These results suggested that there was little agronomic benefit in applying paunch at field equivalent rates higher than 150 kg ha^{-1} of N, and the same was true in terms of grass quality as N content in plant material varied only within a narrow range (Figure 5). From the range of paunch materials used in this study, it appears that highest agronomic efficiencies can be achieved with 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 weeks. 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 stabilized paunch materials on soil C stocks and soil C dynamics are not well understood, and cannot be inferred from this short-term study. This is an aspect that requires investigation, particularly in low C soils (e.g., SOC <1%).

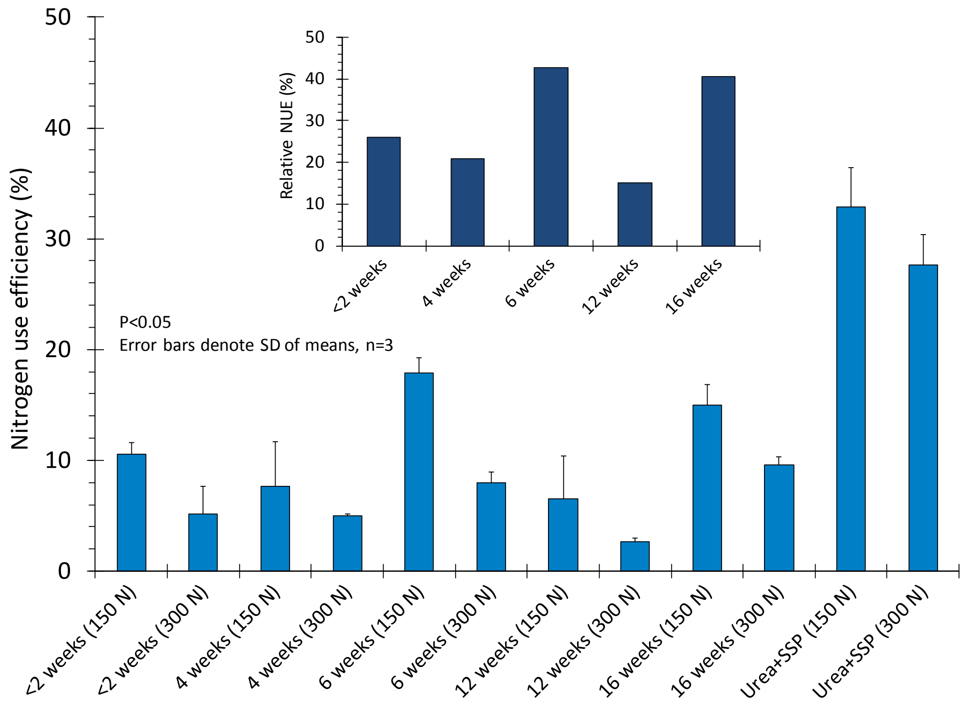

Figure 7: Nitrogen use efficiency (NUE) recorded over three consecutive cuts at 25-day intervals, and after a single application of mineral fertilizers and paunch to ryegrass. Number of weeks denotes compost age, followed by N application rate in kg per ha (field equivalent). Superimposed figure shows NUE of paunch relative to NUE of mineral fertilizer treatment (averaged NUE over the two N application rates used in this study). SSP is single superphosphate.

Fertilizer Replacement Value of Paunch

Mean values (±SD) of N fertilizer replacement value (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 optimizing nutrient recovery in crop and minimizing nitrogen losses following soil application of paunch.

Summary

The main findings derived from this work are summarized below:

1. Risk of weed contamination from soil application of paunch appears to be low. Methods that may enable accounting for dormancy of weed seeds, and viability of seeds may be required to fully discard such a risk,
2. Soil application of paunch increased dry matter yield of ryegrass by ≈30% on average compared with untreated grass, but was approximately 35% lower than the mineral fertilizer treatment. Dry matter yield-to-nitrogen responses were linear within the N application rates investigated, which was observed for 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,
3. Nitrogen use-efficiency (NUE) in paunch was approximately 10% on average (range: 3% to 20%), and between 0.15 and 0.40×NUE_{UREA} depending on paunch type and rate. The quality of harvested plant material in paunch-treated grass was satisfactory (total N_{PLANT} ranged between 2% and 3%) based on reported nutritional requirements for high-producing cattle,
4. The nitrogen fertilizer replacement value of paunch, relative to urea-N, reported an average value of 40±17.1% (single application over three consecutive cuts).

Future Research Requirements

The research areas highlighted here are required to inform soil-, climate- and crop-specific land application rates, optimize agronomic performance and minimize environmental concerns associated with the use of paunch in crop production:

1. Investigate the effect of paunch on soil carbon dynamics and carbon sequestration in soil, and associated effects on nutrient dynamics, particularly nitrogen, including modelling approaches that capture such effects on soil responses and crop productivity,
2. 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, and associated effects on seasonal patterns of nitrogen supply as affected by method of application,
3. Determine the optimum timing of application for both grassland and arable cropping systems, and number of splits within a calendar year or growing season. There is also a requirement to review available methods for land application with a view to improving field operating efficiency, energy requirements of such operation, and minimize impacts on soil, particularly traffic compaction,
4. Conduct detailed economic analyses assessed against alternative options available for disposal of paunch. Such analyses should be undertaken as a cost reduction (avoidance) strategy, and may require the composted product to be partially subsidized to encourage uptake by farmers,
5. The nitrogen fertilizer replacement value of paunch has been derived from a short-term glasshouse experiment using pots, and therefore requires validation in longer-term trials under field conditions.

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