Co-incorporation of biodegradable wastes with crop residues to reduce nitrate pollution of groundwater and decrease waste streams to landfill

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Abstract. Return of high nitrogen (N) content crop residues to soil, particularly in autumn, can result in considerable environmental pollution resulting from gaseous and leaching losses of N. The EU Landfill Directive will require significant reductions in the amounts of biodegradable materials going to landfill. A field experiment was set up to examine the potential of using biodegradable waste materials to manipulate losses of N from high N crop residues in the soil. Leafy residues of sugar beet were co-incorporated into soil with materials of varying C:N ratios, including paper waste, cereal straw, green waste compost and molasses. The amendment materials were incorporated to provide approximately 3.7 t C ha^{-1}. The most effective material for reducing N_2O production and leaching loss of NO_3^- was compactor waste, which is the final product from the recycling of cardboard. Adding molasses increased N_2O and NO_3^- leaching losses. Six months following incorporation of residues, the double rate application of compactor waste decreased soil mineral-N by 36 kg N ha^{-1}, and the molasses increased soil mineral N by 47 kg N ha^{-1}. Compactor waste reduced spring barley grain yield by 73 % in the first of years following incorporation, with smaller losses at the second harvest. At the first harvest, molasses and paperwaste increased yields of spring barley by 20 and 10 % compared with sugar beet residues alone, and the enhanced yield persisted to the second harvest. The amounts of soil mineral-N in the spring and subsequent yields of a first cereal crop were significantly correlated to the lignin and cellulose contents of the amendment materials. Yield was reduced by 0.3 to 0.4 t ha^{-1} for every 100 mg g^{-1} increase in cellulose or lignin content. In a second year, cereal yield was still reduced and related to the cellulose content of the amendment materials but with one quarter of the effect. Additional fertiliser applied to this second crop did not mitigate this effect. Whilst

amendment materials were promising as tools to reduce N losses, further work will need to be carried out to reduce the negative effects on subsequent crops which was not mitigated by applying 60 kg ha $^{-1}$ of fertiliser N.

Introduction

The return of high nitrogen (N) content crop residues to soil, particularly in the autumn, can result in considerable environmental pollution. This can arise both from NO_3^- leaching to water courses, and from the production of nitrous oxide, which has been implicated in global warming (Neeteson & Carton 2001). Crop residues containing high amounts of N are produced by a range of crops, including sugar beet and potatoes, and typically contain between 100 and 200 N kg ha^{-1} (Sylvester-Bradley 1993); the residues of some vegetable brassicas, e.g. Brussels sprouts, can occasionally exceed 300 N kg ha^{-1} (Rahn *et al.* 1992). On this basis it is estimated that sugar beet, potato and vegetable brassica residues, produced on 375,000 ha of land (DEFRA 2002) in the UK, contain 45,000 t N. It is important that this valuable resource is retained and re-cycled into subsequent crops to prevent N losses to the environment. In organic production, there is an even greater need to retain and manage N from crop residues in the soil crop system (Watson *et al.* 2002). There is evidence that even when soils are cool, decomposition of crop residues can still occur rapidly and that mineral-N can be lost from the soil (Rahn *et al.* 2002). Further, where cover crops are planted late, their ability to take up N and reduce leaching can be small (Weinert *et al*. 2002).

Field studies have suggested that short-term rates of N mineralisation and subsequent NO_3^- leaching can be minimised by the co-incorporation of paper waste with crop residues (Vinten *et al.* 1998). Their results demonstrated that there is scope to develop novel strategies for crop residue management based on the addition of substrates to directly influence the activities of the decomposer organisms. Such strategies could be used to either inhibit or stimulate short or long term mineralisation of N and to synchronise N release to the needs of following crops, depending on the nature and quantity of amendment material added.

The addition of readily utilised sources of C to soil has been shown to stimulate denitrification (Weier *et al.* 1993). Adding amendments which reduce mineralisation of N might therefore reduce the potential for loss by leaching, at the expense of increased production of N_2O. Incubation studies (Rahn *et al.* 2003; Motavalli & Diambra, 1997) suggested that materials with a high cellulose or lignin content had the greatest potential to reduce mineralisation of N from sugar beet residues without increasing nitrous oxide production.

The EU Landfill directive 1999/31/EC seeks to reduce the amounts of biodegradable materials being disposed of to landfill to 50 % of the 1995 values by 2013 which suggest that the UK will need to identify a different disposal route for between 6 million tonnes (Mt), by 2010, and 10 Mt by 2013 (The Composting Association 2003); one option is that the material should be spread on agricultural land. However there are constraints on application of such materials to agricultural land, (Directive 75/442/EEC amended by 91/156/EEC). It must be shown that they are spread on land without endangering human health and that they provide an agricultural benefit to the soil. The application of some of these biodegradable wastes to agricultural land may not only have the potential to reduce NO_3^- leaching to comply with the EU Nitrate directive (91/676/EC) but may also assist in helping to reduce the quantities of biodegradable wastes going to landfill. The effects of such materials need to be understood in designing appropriate Action Programmes in Nitrate Vulnerable Zones in fulfilment of this directive.

The objective of this research was to investigate the potential benefits of using biodegradable materials, including materials that might be diverted from landfill such as paperwaste, as amendment materials to reduce N losses from high N content crop residues incorporated into agricultural soils.

Materials and methods

Experimental site and soil properties

A field experiment was set up to test the effects of the most promising treatments from an earlier laboratory incubation experiment (Rahn *et al*. 2003) which investigated the effect of a broader range of materials on potential N losses from sugar beet leaf residues incorporated into soil. The experiment was carried out at Wellesbourne, Warwickshire, England on a sandy loam soil of Dunnington Heath series (Whitfield 1974), chromic luvisol (FAO 1998). The soil had a pH of 6.4 with exchangeable P and K concentrations of 83 and 160 mg l^{-1}, respectively, as determined using standard analytical methods (MAFF 1986). The experimental area had been cropped with winter barley and winter wheat in 1997/8 and 1998/9 respectively. The site was fertilised with compound fertiliser supplying 60 kg/ha P_20_5 in autumn of each year and 60 K_20 in 98 and 90 in 99 and 75 in 2000.

Experimental design

The experiment was set up to investigate the effect of co-incorporation of sugar beet leaves with 6 organic amendments. The treatments were as follows:

1. No residues or amendment material
2. Sugar beet residues only (control)
3. Molasses (a by-product from sugar beet refining)
4. Compactor waste (a recalcitrant waste product of waste paper recycling)

5. Double rate compactor waste (7.5 t ha^{-1} C)

6. Compost (composted local authority green waste)

7. Paper waste (from the paper recycling industry).

8. Wheat straw (grown at Warwick WHRI)

Treatments 3-8 also received the same amount of sugar beet residues as treatment 2.

Amendments were incorporated on the 7th October 1999 with all treatments and on 14 January 2000 where treatments 1, 2 3 and 5 were applied to different plots..

For the first season treatments were arranged in four randomised blocks and each plot was 8 * 3.6m . In the second season, 2001 two of the experimental blocks received fertiliser and two blocks remained unfertilised.

Statistical analysis was carried out using Genstat (Payne et al 2007) In the first season the analysis was based on 11 treatments and 4 replicates providing 33 df for the estimation of error. In the second season where N was applied to the blocks a spit plot analysis was used where the number of degrees of freedom for fertiliser applied was 2, and for the amendment treatments was 22.

Amendment materials

The amendment materials were selected for their differences in biochemical quality and their potential N immobilising ability (Table 1). Materials with a wide C:N ratio were selected to immobilise N and those of a narrow C:N to stimulate net mineralisation. Materials were also chosen because of ready availability. Two types of paperwaste were selected for their potential N immobilising capacity; these were 'compactor' waste and 'paper' waste, which were obtained from the cardboard and paper recycling industry respectively. Wheat straw was collected from a recently harvested field at WHRI

Wellesbourne. For narrow C:N materials, compost was obtained from Worcestershire County Council and liquid molasses from the sugar beet refining industry. Although also sold as an animal feed, molasses was chosen for its high carbohydrate content and potential to stimulate rapid microbial growth and decomposition.

The amendment materials were applied at amounts intended to supply 3.7 t C ha^{-1}, although the actual rate varied between 3.2 and 3.8 t C ha^{-1} (Table 1). It was assumed that only one third of the carbon would be biochemically active and that the soil microbial biomass had a C:N ratio of 7:1, similar to that used for unamended soils (Joergensen & Raubach, 2003; Ocio & Brooks 1990, Jenkinson 1988), so it was calculated that 181 kg of N would be immobilised by adding the amendment materials. Dry amendment materials were spread by hand while the molasses was diluted with water and sprayed on to ensure even coverage. The amendment materials were co-incorporated with 42 t ha^{-1} of fresh sugar beet leaves (containing 117 kg ha^{-1} N) in October 1999. Treatments 1, 2, 3 and 5, were repeated in January 2000 with 41 t ha^{-1} as fresh sugar beet leaves (containing 191 kg ha^{-1} N). The leaves of sugar beet were obtained from a commercial crop grown on a neighbouring farm. The chemical composition of the two batches of leaves did not differ significantly. The quality characteristics of the sugar beet used in October 1999 is shown in Table 1. Materials were co-incorporated to a depth of 20 cm using a mechanical spading machine. Treatments were arranged in four randomised blocks and each plot was 8 x 3.6 m.

Chemical quality of amendment materials

The characteristics of each material were determined by measuring carbohydrates, cellulose and lignin content using a proximate analysis based on H_2SO_4 hydrolysis, as described by Rahn *et al.* (1999). Water-soluble phenolics and total C:N ratio were determined as described in Bending *et al.* (1998). The analyses were carried out on triplicate samples. The characteristics of materials used for the October and January incorporation dates were similar. Data from material used for the October incorporation date is shown in Table 2.

Soil sampling and analysis

Levels of mineral-N to 90 cm were measured on all plots on 4th October, 21st October, 7th December in 1999, 10th January, 14th April, 1st and 15th November in 2000, 14th of March and 20th of August 2001. Two soil cores were taken from three layers (0-30, 30-60 and 60-90 cm) per plot. Nitrate and ammonium concentrations were determined using continuous flow analysis (MAFF 1986) after extraction with 0.5 M K_2SO_4.

Following the October incorporation, overwinter leaching was estimated using porous cups (three per plot) on treatments 1-4 which allowed the NO_3^- concentration of water draining below 60 cm to be determined during the winters of 1999/2000, 2000/2001 and 2001/2002. Cups were sampled after every 25 mm rainfall after the onset of field capacity and drainage volume was assumed to equal rainfall after field capacity had been reached. The results were interpreted using methods described in Lord *et al.* (1993).

Losses of N_2O were assessed following the October and January incorporation dates using four automated closed chambers provided by Scottish Agricultural College with single chambers being used on treatments, 1, 2, 3 and 5 following the incorporation of residues and amendments in October and January. The procedures for operation of these units and analysis of samples were as described by Scott *et al.* (1999).

Crop growth and uptake of N following reside and amendment incorporation

The mineral-N remaining after two consecutive winters was assessed by drilling spring barley on 4th of May 2000 (cv. chariot) and 19th April 2001 (cv. Pearl), respectively. No N fertiliser was applied in 2000, but in 2001, 60 kg ha^{-1} N as NH_4NO_3 was applied to two of the four experimental blocks on 27th April 2001.

Yield and total N uptake of the two cereal crops was determined in order to estimate the recovery of N from the co-incorporated materials and soil samples were used to assess the continuing potential of the amendment materials to immobilise N mineralised during the spring and early summer of 2001.

Yield was determined by plot combine on 29/08/00 and 16/08/01, harvesting at least 11.2 m^2 per plot, from which area all grain straw and stubble was collected and weighed. Sub-samples of at least 100 g were taken for drying at 80^{o}C for 48 hours. The N content of the dried material was determined by total combustion using a C/N autoanalyser (Leco Corporation, Michigan, USA).

Results

Soil mineral-N

Prior to the incorporation of the amendment materials in October 1999, mineral-N in the 0-30 layer was 29.7 kg ha^{-1} (Figure 1). Within a month of the incorporation of sugar beet residues, soil mineral-N levels had increased by over 6 kg ha^{-1} in comparison to soils receiving no residue, and levels remained elevated until April 2000. Where molasses were co-incorporated with the sugar beet residues, there was rapid mineralisation, with mineral-N levels being 10 to 15 kg ha^{-1} higher than the sugar beet alone treatment between a month and 6 months following incorporation. Levels of mineral-N following co-incorporation of compactor waste were 20 kg ha^{-1} lower than the soil receiving sugar beet residues alone by mid November 1999, although by April 2000 amounts of mineral-N at 0-30 cm depth had returned to levels found in the sugar beet alone treatment.

In April 2000, six months following incorporation, analysis of soil mineral-N at 0-90 cm depth showed that the addition of sugar beet residue had increased mineral-N levels by 16 kg ha^{-1} (Table 2). In comparison to soil receiving sugar beet residues alone, co-amendment with straw and compactor waste reduced soil mineral-N by 25 and 15 kg ha^{-1} respectively, with the double compactor waste reducing mineral-N by 36 kg ha^{-1}. Paperwaste had no net effect on mineral-N, while molasses and compost increased soil mineral-N by 46 and 11 kg ha^{-1}, respectively. The January incorporation of molasses and compactor waste had similar effects on soil mineral-N as the October incorporation. Amounts of mineral-N in April following the October incorporation were significantly correlated ($p>0.05$) with concentrations of lignin and cellulose in the amendment materials ($r=-0.91$ and -0.86 respectively).

Following the October incorporation, soil mineral-N levels to 90 cm depth were around 60 kg ha^{-1} N, in the November/March of 2000/01 and were not significantly affected by the amendment materials or sugar beet residues incorporated in the autumn of 1999. Similarly following harvest in August 2001 there were no significant effects of amendments, or fertiliser on the mineral-N level in the 0-90 cm soil layer, which remained around 60 kg ha^{-1} N (data not shown).

Leaching losses

For the October incorporation, compared to soil which received no residues, incorporation of sugar beet alone reduced amounts of N leached between Nov-Dec 1999, but increased amounts leached between Jan-Feb 2000 (Table 3). Compared to the sugar beet alone treatment, molasses increased, and compactor waste decreased, the N concentration of leachate. The increased leaching following molasses incorporation was evident from the first sampling date in November 1999 and continued until February 2000. For compactor waste, leaching losses were higher than the sugar beet alone treatment until December 2000, and subsequently declined to between a half and a third of levels in the sugarbeet alone treatment.

Overall, in the 1999/2000 season there was no significant difference in amounts of N leached in the no residue and sugarbeet alone treatments, with 56 and 60 kg N ha^{-1} lost respectively. However, leaching losses in the molasses and compacter treatments were significantly ($P<0.001$) different to the other treatments, at 72 and 38 kg N ha^{-1} . In the following winter the total amounts of leaching ranged from 29 to 36 kg N ha^{-1} with no significant treatment differences in 299 mm of drainage. There were no significant differences between treatments. In the 2001/02 the second winter after the amendments were applied the leaching amounts varied from 23 – 33 kg N ha^{-1} and not significantly different in 124 mm of drainage. The application of 60 kg N ha^{-1} did not significantly affect the amounts of N leached.

Gaseous losses of N

N_2O losses were monitored for both the October 1999 and January 2000 incorporation dates on selected treatments using un-replicated chambers. Treatment effects on N_2O losses were similar at the two sampling dates, and only data from January 2000 is shown

(Fig 2). Following January incorporation, there were peaks in evolution of N_2O from the soil alone treatment after 36 and 72 hours, with peaks of 300-400 µg N_2O m^2 hr^{-1} . In the sugar beet treatment, there were peaks in N_2O production evolution after 72 and 144 h, with peaks of 700 and 350 µg N_2O m^2 hr^{-1} evolved. In the sugar beet plus compactor treatment, there was a single peak 150 µg N_2O m^2 hr^{-1} after 72 h, with. In contrast, N_2O losses in the molasses treatment were substantial, with a peak of over 1500 µg N_2O m^2 hr^{-1} after 36 h, with levels remaining above 200 µg N_2O m^2 hr^{-1} until 120 h, when there was a sharp increase to 2800 µg N_2O m^2 hr^{-1}. Levels of N_2O returned to those seen in the other treatments only after 218 h. The overall amounts of N lost as N_2O were at most 3 kg ha^{-1} over the entire period of monitoring where molasses had been co-incorporated.

Grain Yield

Following the October incorporation, sugar beet residues increased grain yield by 12 % relative to unamended soil at the first season after incorporation, in 2000 (Table 4). Co-incorporation of paperwaste and molasses with sugar beet increased yield by a further 11 and 20 %, respectively. Straw and compactor waste reduced grain yield by 47 and 21 %, respectively, while the double compactor treatment reduced grain yields by 63 % compared to sugar beet residue alone. Following January incorporation, yield in the absence of residues or amendments was only 1.6 compared with 2.1 t ha^{-1} with October cultivations. Yield was increased markedly by sugar beet incorporation. Compactor waste reduced yield by 53 % and the application of molasses increased yield, but only by 8 % compared with residues alone.

Cellulose and lignin content of the amendment materials were significantly ($P<0.05$) correlated with grain yield (r= -0.85 and -0.83 respectively). Variations in yield were significantly correlated (r=0.90, P<0.05) with soil mineral-N in April which were also related to lignin and cellulose contents.As the concentrations of cellulose and lignin in the amendment materials increased, yield decreased by 0.4 (± 0.1) and 0.3 (± 0.09) t ha^{-1} respectively, for 100 mg g^{-1} cellulose and lignin respectively, (Figure 3a, 3b).

In 2001, where no new N fertiliser had been applied there was a 21 % decrease in barley yield where no sugar beet residues had been incorporated in 1999, relative to soil that had received sugar beet residues (Table 4). Where the single rate of compactor and straw were incorporated, grain yield was reduced by 20 %. However, where the double rate of compactor was applied, yield was only reduced by 3 %. Incorporation of molasses, compost and paper waste increased grain yield by 28, 41 and 38 %, respectively. Where amendments and residues had been incorporated in January the patterns were different, with yield being boosted by both molasses (+239 %) and compactor waste (+50 %).

Where 60 kg ha^{-1} N fertiliser had been applied to the October 1999 treatments, the effects of the amendments on yield were smaller compared to where no N had been added, with the differences in grain yield compared with sugar beet residues alone -14, -13, -16, +6, +16, -1, -4 % for no residue, compactor waste, double rate compactor, molasses, paper waste compost and wheat straw, respectively. With January incorporation there were increases in yield of 4 and 27 % respectively where compactor and molasses had been applied.

Following October incorporation variations in yield in the second cereal crop in 2001 were again significantly (P<0.05) correlated with the cellulose content of the amendment materials (r= -0.90). Figure 5a shows the effect of increasing concentrations of cellulose in the amendment materials on yield, with and without fertiliser applied. The slope of the relationships was not affected by the application of fertiliser N. When both lines are taken into account over 96% of the variance in yield is accounted for (df =9). For every 100 mg g^{-1} increase in concentration of cellulose, yield was reduced by 0.11 (± 0.02) t ha^{-1}, correspondingly increased lignin contents reduced yield by 0.12 (± 0.04) t ha^{-1}. This data indicates that the amendment materials were still having an effect on yield in 2001, but that it was up to four times less than seen in 2000.

N Uptake

At the first harvest of spring barley in 2000 the variation in plant N uptake was closely related to grain yield (r^2=0.94). Compared to application of sugarbeet alone, compost, compactor, double compactor and straw reduced N uptake by 9, 25 63, and 48 % respectively (Table 5). In contrast, molasses increased N uptake by almost 32 %. Paperwaste had no effect on N uptake. Where sugar beet had been incorporated in January, N uptake was similar to that taken up following the October incorporation. Compactor waste reduced N uptake by 55 %, and molasses stimulated N uptake by 9%

Plant N uptake at the 2000 harvest was significantly ($P<0.05$) correlated with lignin and cellulose (r=-0.88 and -0.83 respectively) N uptake was reduced by increasing concentrations of lignin or cellulose, falling by 9 (±2) and 6 (±2) kg ha^{-1} for each 100 mg g^{-1} change in concentration respectively.

At the second harvest in 2001, N uptake was reduced by 24% where no residue had been incorporated, compared to the control with sugar beet alone (Table 5). Incorporation of compactor and double compactor reduced N uptake by 13 and 15% respectively. Addition of paperwaste and compost increased N uptake by 31 %, and molasses by 21%. Where amendments and residues had been applied in January, compactor and molasses increased crop N uptake by 30 and 106 % respectively.

Where 60 kg ha^{-1} N fertiliser had been applied, N uptake was significantly increased, and the effects of the amendment materials on N uptake were smaller relative to when no fertiliser had been applied. Where residues had been incorporated in October, molasses and paperwaste increased N uptake by 4 and 16 % respectively. Single and double compacter waste reduced N uptake by 14 and 18 % respectively. Where amendments were incorporated in January, compactor and molasses waste increased N uptake by 14 % and 33 % respectively.

N uptake at the 2001 harvest, like yield, was significantly correlated to cellulose content, r= -0.93, P<0.01). Similarly the relationships were not affected by the addition of fertiliser N, although the influence of the concentration of cellulose on N uptake at the 2001 harvest was lower than at 2000, with an change in N uptake of 2 (±0.4) kg N ha^{-1} for each 100 mg g^{-1} change in cellulose concentration (Figure 4b).

N Balance during growing season

During 2000, straw, compactor waste and paperwaste had no effect on the net N balance between April and harvest (Table 6). However for the molasses and compost treatments there was a large negative N balance, which amounted to -33 and -27 kg N ha^{-1} respectively, indicating that large amounts of net immobilisation had occurred. Net N balance was significantly correlated with % N, cellulose and lignin content (r=-0.88, -0.82 and -0.88 respectively). More N was immobilised following incorporation of materials in January although there were no significant differences between treatments.

In the 2001 season, in the absence of fertiliser-N all treatments showed a positive net N balance. In the October treatments, in plots without N fertiliser, N balance for compost and compactor were 12 and 14 kg ha^{-1} higher than for the sugarbeet alone treatment, but there was no significant difference with the other treatments. N balance was higher for the January incorporation, and both molasses and compactor waste resulted in an elevated n balance relative to the sugarbeet alone treatment.

Applying fertiliser-N led to largely negative N balances, suggesting N immobilisation, although netN was still mineralised where sugar beet or sugar beet and paperwaste had been incorporated. With October incorporation more N was immobilised where compactor waste had been incorporated or in the absence of residues. Similar results were seen for the January incorporation.

Discussion

The data clearly demonstrates that co-incorporation in the field of crop residue materials with a broad range of materials with different chemical properties can have a significant impact on soil N cycling processes, and in particular, that the size and direction of the impact is predictable and largely dependent on the lignin and cellulose content of the amendment material.

Several laboratory studies have investigated the effect of amendments of varying composition and complexity on mineralization of N from crop residues. Vinten *et al.* (2002), used incubation experiments in which residues were co-incorporated with pure cellulose, glucose or straw as sources of C. In common with high C:N ratio materials in our study, they noticed substantial initial immobilisation of mineral-N which was largest from glucose followed by cellulose and straw. In contrast, lower C:N materials such as molasses showed no such immobilisation.

The effects of the amendment materials on net N mineralization following incorporation of sugarbeet residues were similar to those in an earlier laboratory incubation study (Rahn *et al.* 2003). Decreased net mineralization caused by several materials, including compactor waste, was explained, at least in part, by increasing immobilisation of N into the biomass. In the experiments of Vinten *et al.* (2002) the immobilisation of all N could not be explained by bacterial biomass, but where cellulose content was higher more fungal biomass appeared to have been responsible for the immobilisation.

Our data confirm the results from earlier laboratory incubation experiments using the same materials (Rahn *et al*. 2003) and those of Motavalli & Diambra (1997), in which total N, lignin, cellulose, C:N and cellulose:N ratios were shown to be appropriate to estimate net mineralisation following co-incorporation of paperwaste and other waste materials with crop residues into soil. In addition our findings support those of Vinten *et al*. (1998) where the release of N was based on the decomposability of carbon compounds contained in paper mill sludge, and not simply on C:N ratio.

In common with our study, Vinten *et al. (*1998) also identified large reductions in N leaching with the addition of paper mill waste to soils in the first season after application. There is clearly some potential for longer term consequences of repeated application of such wastes, with the possibility that immobilised N could stimulate out of season mineralisation and increase NO_3^- leaching in the longer term. However our data showed no evidence that any of the materials stimulated additional leaching in the second winter.

In earlier laboratory incubation experiments with these amendment materials, Rahn *et al.* (2003) showed that co-incorporation of molasses with sugarbeet residuess stimulated N_2O formation for less than 24 h relative to soil receiving sugar beet residues, with amounts of N_2O produced depending on soil type, with higher quantities in a sandy-loam relative to a clay-loam. Similarly, Yang *et al.* (2002) found rapid increases in N_2O emissions immediately following incorporation of composts and manures into soil. Furthermore, in laboratory incubation studies Chaves *et al.* (2005) found that a variety of high C:N materials including sawdust and green compost compost reduced N_2O production during decomposition of celery residues, although a low C:N ratio paperwaste material increased N_2O production. Increased emission of N_2O following co-incorporation of narrow C:N paperwastes with crop residues has been shown several times (Vinten *et al.* 1988; Baggs *et al.*, 2002). Denitrification is dependant on various parameters, including the availability of NO_3^- , labile organic compounds, and the N_2O/NO_3^- ratio (Weier *et al.* 1993). The stimulated production of N_2O by low C:N substrates, including molasses in the current study, clearly reflects the rapidly decomposable nature of these materials. The reduced denitrification that can occur following addition of high C:N ratio materials, including compactor waste (Rahn *et al.*, 2003; Chaves *et al.* 2005) probably reflects immobilisation of NO_3^- within the microbial biomass during decomposition (Beauchamp, 1997). Whilst the losses measured in our study were agronomically small even where molasses was applied N_2O is a potent greenhouse gas IPCC (2006)

In the study of Aitken *et al.* (1998) the application of 100 t ha^{-1} of de-inked paper mill sludge (DPMS) with C:N of 86 reduced cereal yield one year after application. However, in the second year there were no significant effects on grain yield, and by the third season more soil N was seen where DPMS had been applied suggesting some remineralisation of N. Vagstad *et al.* (2001) showed that barley yields increased following the incorporation of static piles of paper waste into soil in Norwegian field studies, although these materials had a narrow C:N ratio (20:1). Where paperwaste materials had a wider C:N ratio (30:1), grain yields of the following crop were reduced. These effects were only observed in the first year after incorporation, and yield effects were small in following seasons. In our experiments, where high C:N compactor waste had been applied there were still reductions in yield at the second crop harvest even where fertiliser had been applied. However, there was evidence for remineralisation and enhanced grain yield in soil receiving materials of lower lignin content such as paperwaste, molasses and green compost. Motavallii *et al.* (2000) also found that where wide C:N (1235) paperwastes had been incorporated into field soils there were similar yield reductions, with an estimated fertiliser N application of over 250 kg ha^{-1} needed to overcome the yield reduction.

In the second growing season the correlations between the quality of the organic matter in the amendments and net N mineralisation were less clear, which suggests the increasing effects of other factors on N dynamics. One of the factors is likely to be remineralisation of N. Eriksen (1999) did see increased amounts of remineralisation of N in his experiments where the highest rates of municipal solid waste had been applied to soils**.** Mitchell *et al*. (2000) also showed that seasonal effects on can have a large effect on N mineralisation with complex interactions between temperature and soil processes.

The amounts of carbon incorporated with crop residues needs to be adjusted for effective reduction of leaching and also to reduce any negative effects on yield and to control later remineralisation of N. De Neve *et al* (2004) found that the addition of molasses could be used to stimulate remineralisation of immobilised N in a laboratory study but Chaves *et al.* (2007) demonstrated that it is not easy to stimulate remineralisation of immobilised materials in the field. Beauchamp (2002) indicated that there were other aspects of the chemical quality of paperwastes such as their content of fatty acids and PCBs which should be considered prior to application to land, although in their samples of deinked paper waste these components were not at a significant level and composting reduced the levels further.

Conclusions

- Where low quality amendment materials were co-incorporated with sugar beet residues the concentration and amount of N leached in the first winter was significantly reduced.
- Where NO_3^- leaching was reduced where low quality amendment materials had been co-incorporated, grain yield of the subsequent cereal crops was reduced.
- The grain yields and nitrogen uptake in the first season were more closely related to the quality of the amendment materials as measured by the contents of cellulose and lignin rather than simple assessment of N or C:N ratio.
- The cellulose and lignin content in the amendment materials also affected the yields and N uptake of a second cereal crop but the effects were about a third to a quarter those seen in the first season. The effect was not mitigated by the application of 60 kg/ha fertiliser N.
- Whilst the application of amendment materials have the potential to reduce losses of N, before its wider use experiments will need to be carried out testing the effects of

different rates and methods of mixing so that excess N can be immobilised but not in competition with plant requirement.

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Table 1. Chemical characteristics of leaf and amendment materials based on dry weight, and the fresh weight, and amount of C and N applied in the amendment materials

	% DM	C:N	% N	%C	WS carb[a] (mg g^{-1})	WS phen[b] (mg g^{-1})	Cellulose (mg g^{-1})	Lignin (mg g^{-1})	Fresh weight applied t ha^{-1}	C applied kg ha^{-1}	N applied kg ha^{-1}
Leaf Material											
Sugar beet	14.1	8.6	1.96	38.0	106	12	126	153			
Amendments											
Molasses	78.9	16.0	2.30	37.1	910.0	14	2	3	12.2	3629	221
Compactor	31.3	350	0.14	48.2	14.0	2.6	492	291	23.6	3556	10
Paperwaste	51.4	71.0	0.32	22.5	3.7	1.4	93	179	28.1	3248	46
Compost	71.6	14.0	1.07	14.5	3.2	2.1	50	161	35.3	3666	271
Wheat straw	70.3	82.0	0.54	44.0	5.2	11	344	428	12.2	3776	46

[a] Water soluble carbohydrate
[b] Water soluble phenolics

Table 2 Soil mineral nitrogen at 0 – 90 cm depth (kg ha $^{-1}$)

	April 2000 Soil mineral N (kg ha^{-1})	Harvest (August 2000) Soil mineral N (kg ha^{-1})
October incorporation		
No residue	83.5	46.1
S Beet alone	99.4	46.0
+ Molasses	146.0	52.8
+ Compactor	84.2	48.6
+ Double Compactor	63.8	49.9
+ Paperwaste	100.3	48.8
+ Compost	111.1	44.0
+ Wheat straw	74.5	56.1
January incorporation		
Control	96.1	46.9
S Beet only	109	44.2
+ Molasses	126.3	52.1
+ Compactor	75.3	42.4
ANOVA		
p =	p(SED)	p(SED)
Amendment	<0.001(9.47)	0.166(4.62)

Table 3 Nitrate leached in the first winter following October incorporation of amendment and residue expressed as concentration (mg NO_3 L^{-1}). Overwinter drainage = 150 mm, df=28.

Year	1999			2000		
	25 Nov	10 Dec	23 Dec	5 Jan	8 Feb	28 Feb
No Residue	154	177	161	195	172	160
S Beet alone	98	141	148	216	226	233
+ Molasses	162	187	167	222	266	265
+ Compactor	155	186	127	120	71	83
ANOVA						
p	0.05	0.17	0.02	0.002	0.001	0.001
S.E.D.	24.0	22.6	13.0	26.7	36.1	34.9

Table 4 Grain Yields of Barley (t ha^{-1}) at 85% DM. Statistical analysis based on 33 df for 2000, and 2, 11 and 11 df for testing nitrogen, amendment and their interactions in 2001.

	2000 Grain Yield (t ha^{-1})	2001 Grain Yield (t ha^{-1})	
Fertiliser (kg ha^{-1})	0	0	60
October incorporation			
No residue	2.10	0.73	2.07
S Beet alone	2.36	0.92	2.42
+ Molasses	2.83	1.18	2.56
+ Compactor	1.86	0.74	2.11
+ Double Compactor	0.87	0.89	2.03
+ Paperwaste	2.59	1.27	2.82
+ Compost	2.32	1.30	2.40
+ Wheat straw	1.25	0.77	2.32
January incorporation			
Control	1.58	0.58	1.82
S Beet only	2.73	0.66	2.28
+ Molasses	2.96	1.58	2.90
+ Compactor	1.29	0.99	2.36
ANOVA			
p =	p (SED)	p(SED)	
Nitrogen	nd	0.009(0.133)	
Amendment	<0.001(0.352)	<0.001(0.186)	
Interaction	nd	Ns(0.285)	

Table 5 Nitrogen uptake in Barley crops (straw grain and stubble) measured at harvest (kg ha^{-1}). Statistical analysis based on 33 df for 2000, and 2, 11 and 11 df for testing nitrogen, amendment and their interactions in 2001.

	2000 Uptake (kg ha^{-1})	2001 Uptake (kg ha^{-1})	
Fertiliser (kg ha^{-1})	0	0	60
October incorporation			
No residue	39.9	14.5	42.0
S Beet alone	46.1	19.0	51.5
+ Molasses	60.7	23.0	53.5
+ Compactor	34.6	16.5	44.5
+ Double Compactor	17.2	18.0	42.0
+ Paperwaste	47.1	25.0	59.5
+ Compost	40.6	25.0	51.5
+ Wheat straw	24.3	18.0	51.0
January incorporation			
Control	30.7	13.5	38.5
S Beet only	51.9	15.0	47.5
+ Molasses	56.6	31.0	63.0
+ Compactor	23.4	19.5	54.0
ANOVA			
p =	p(SED)	p(SED)	
Nitrogen	nd	0.004(1.80)	
Amendment	<0.001(7.02)	<0.001(3.50)	
Interaction	nd	Ns(4.94)	

Table 6 N Balance between April and harvest in 2000 and March and harvest in 2001. (Starting values in spring based on mineral N 0-90cm, values in harvest on soil mineral N 0-90 cm and N uptake of cereal) Statistical analysis based on 33 df for 2000, and 2, 11 and 11 df for testing nitrogen, amendment and their interactions in 2001.

	2000 N Balance (kg ha^{-1})	2001 N Balance (kg ha^{-1})	
Fertiliser (kg ha^{-1})	0	0	60
October incorporation			
No residue	2.5	14.0	-19.1
S Beet alone	-7.3	16.0	10.0
+ Molasses	-32.6	16.0	-0.5
+ Compactor	-1.0	28.0	-13.7
+ Double Compactor	3.4	22.0	-12.6
+ Paperwaste	-4.5	23.6	10.4
+ Compost	-26.6	30.0	-4.7
+ Wheat straw	5.9	16.3	-9.7
January incorporation			
Control	-18.5	38.5	-15.5
S Beet only	-12.8	47.5	-15.4
+ Molasses	-17.5	63.0	5.4
+ Compactor	-9.5	54.0	-19.7
ANOVA			
p =	p(SED)	p(SED)	
Nitrogen	nd	0.003(1.5)	
Amendment	<0.001(8.77)	ns (7.3)	
Interaction	nd	ns(10.0)	

Figure legends

Figure 1. Effect of sugar beet residue and amendments on soil mineral-N (0-30 cm depth) following incorporation in October 1999. Errors are SED.

Figure 2 Nitrous oxide emission (N_2O) following incorporation of sugar beet residue and amendments in January 2000. Data reflects single replicates for each treatment

Figure 3 Relationships between Grain Yield 1st harvest and properties of the amendment materials, a) acid cellulose, b) Lignin. Trendline shown for October incorporated amendments (closed symbols) where regression significant ($p > 0.05$). Open symbols January Incorporated Amendments

Figure 4 Relationship between cellulose content of amendment materials with grain yield of spring barley (4a) and nitrogen uptake (4b) at 2nd harvest. Closed and open symbols data from October incorporation and January incorporation respectively. Square symbols with fertiliser, Circles without. Dotted line represents trendline for October incorporated treatments only with 60kg/ha fertiliser applied in the spring. Solid line – no spring fertiliser

Figure 1

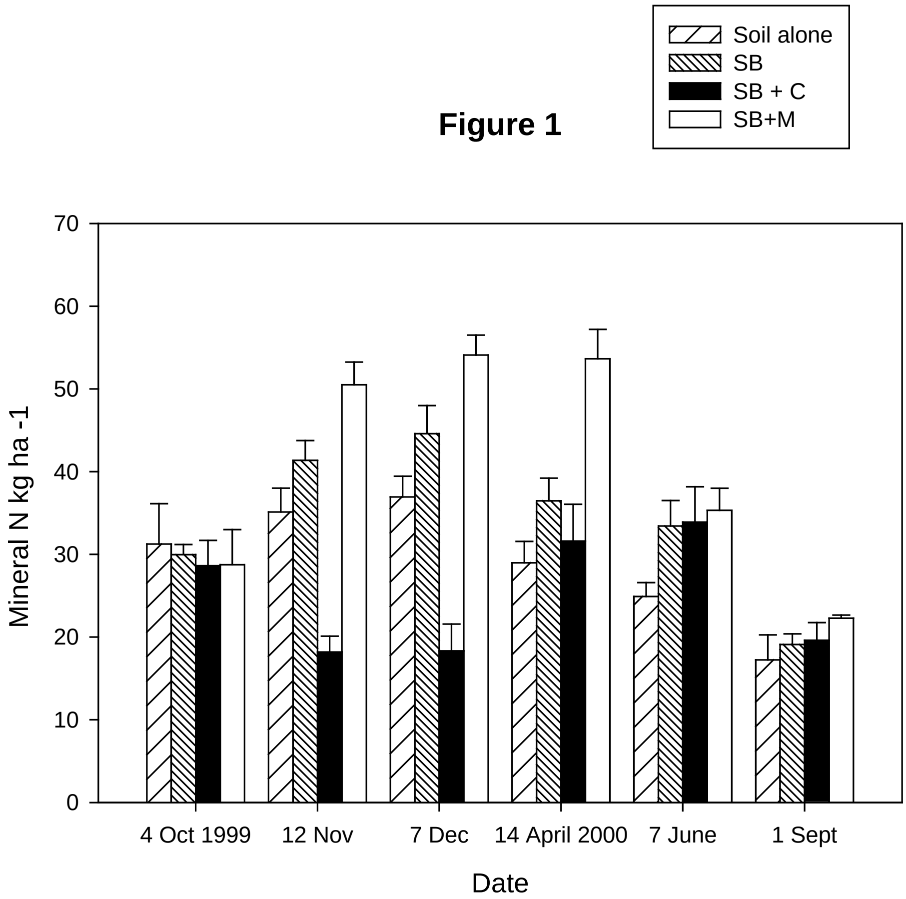
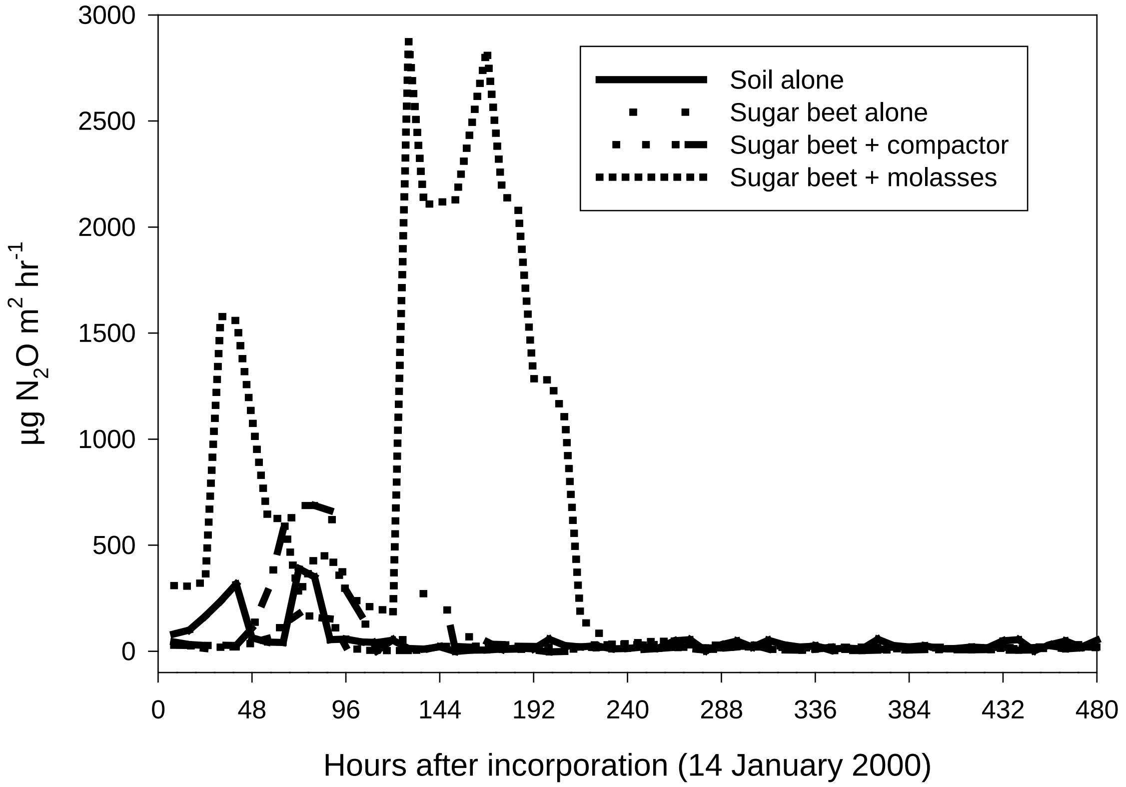

Soil alone
SB
SB + C
SB+M
70
60
50
40
30
20
10
0
Mineral N kg ha -1
4 Oct 1999
12 Nov
7 Dec
14 April 2000
7 June
1 Sept
Date

Figure 2


3000
2500
2000
1500
1000
500
0
μg N2O m2 hr-1
0
48
96
144
192
240
288
336
384
432
480
Hours after incorporation (14 January 2000)
Soil alone
Sugar beet alone
Sugar beet + compactor
Sugar beet + molasses

1

Figure 3a

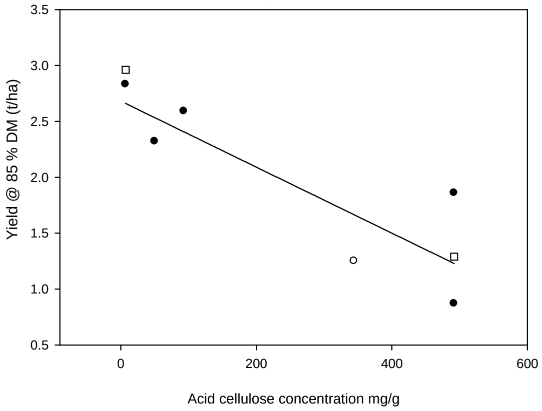


Figure 3b

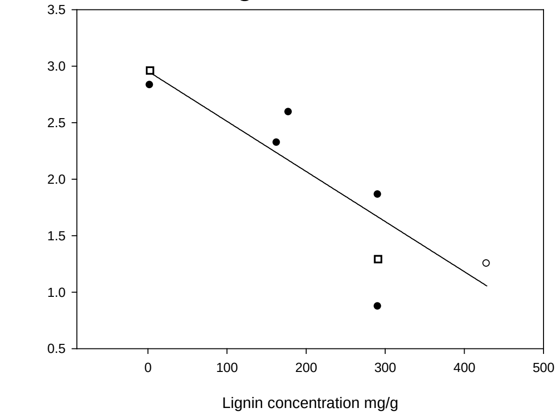


Figure 4a

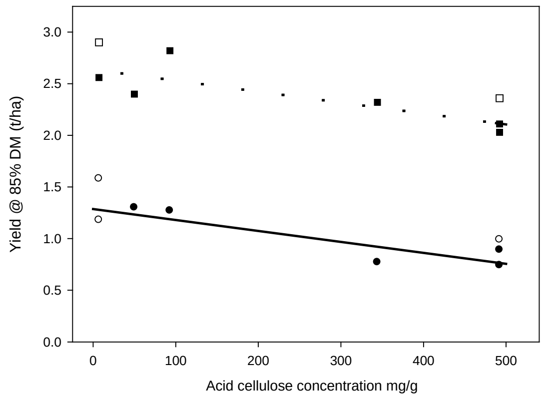


Figure 4b