2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation

Paper Number: 131620220

Field studies on the value of organomineral fertilisers as amendments for perennial ryegrass (*Lolium perenne* L)

D.L. Antille*

Cranfield University, School of Applied Science, Building 37, MK43 0AL, Bedford, UK. *Corresponding author (Present address): University of Southern Queensland, National Centre for Engineering in Agriculture (NCEA), Building Z2, West Street, 4350 Toowoomba, QLD, Australia. Email: d.l.antille@gmail.com

R. Sakrabani

Cranfield University, School of Applied Science, Building 37, MK43 0AL, Bedford, UK.

R.J. Godwin

Harper Adams University, Newport, TF10 8NB, Shropshire, UK.

**Written for presentation at the
2013 ASABE Annual International Meeting
Sponsored by ASABE
Kansas City, Missouri
July 21 – 24, 2013**

Abstract. *A field-scale trial was established to investigate the agronomic efficiency of novel organomineral fertilisers (OMF) produced from nutrient-enriched sludge granules. Two OMF formulations were tested:* OMF_{15} *(15:4:4) and* OMF_{10} *(10:4:4) which were compared with urea and biosolids granules applied to a grass crop over a period of two years. The fertilisers were applied at N rates in the range of 0 (control) to 250 kg* ha^{-1} *at regular increments of 50 kg* ha^{-1}*. Results showed that the calculated agronomic efficiencies with OMF were in the range of 25 to 35 kg* kg^{-1} *which were approximately double than those of biosolids and comparable to those obtained with urea (range of 30 to 37 kg* kg^{-1}*). Olsen's P in OMF-treated soil did not show significant changes (*$P>0.05$*); therefore, soil P Index was not affected. This result supported the reasons for the proposed OMF formulations and demonstrated the advantage of the products compared with biosolids which resulted in significant (*$P<0.05$*) increases in Olsen's P. It was also demonstrated that the application of OMF at rates equivalent to the optimum N rate for the grass-soil system should not induce significant changes in soil P Index in the longer-term including application to soils with already satisfactory P levels. Fertiliser application strategies (N rates and timing of OMF application) are discussed which will enhance agronomic and environmental performance.*

Keywords. *Urea, biosolids granules, organomineral fertilisers (OMF), ryegrass, Olsen's P, soil P Index.*

Introduction

In Europe, the gradual implementation of the Urban Waste Water Treatment Directive 91/271/EEC (CEC, 1991) has resulted in increasing amounts of sewage sludge that require safe disposal (EC, 2012). Estimates for 2005 indicated that the European Community produces approximately 9 million tonnes per year of sewage sludge (dry solids) which represents an increment of about 65% compared with 1992's levels (EC, 2012). The increase in sewage sludge production also responds to the steady growth of the population and therefore the number of households connected to sewerage systems. The use of tertiary treatment for the removal of nutrients from wastewaters is a requirement in sensitive areas before treated water is recycled to the environment (DEFRA, 2002). Hence, further requirements for enhanced treatment of sewage effluents can arise from future designations of sensitive waters under the provisions of the Directive (CEC, 1991) which will result in increased sludge production. In this respect, Edge (1999) estimated that phosphorus removal by precipitation increases sludge production by about 10% to 25% compared with sludge that receives secondary treatment only. The water industry recognises significant cost advantages in recycling biosolids through agriculture compared with alternative more expensive disposal options such as landfill and incineration. Estimates (Antille, 2011 with 2007 figures) indicated that in the NW region of England, agricultural recycling costs wastewater companies approximately GBP150 per tonne of raw sludge (dry solids), and landfill and incineration are about GBP200 and GBP250 per tonne of raw sludge (dry solids) respectively. These figures include finance and depreciation. The latter two disposal options are regarded as less sustainable practices (Petts, 1994) therefore being increasingly restricted by environmental legislation (Moseley et al., 1998) such as in the EU Landfill Directive 99/31/EC (CEC, 1999).

In the NW region of England, the disposal strategy of wastewater operators is based upon a dual approach of recycling to farmland and incineration which take, approximately, 70% and 30% of the total sludge production respectively (Antille, 2011). The relatively high reliance on recycling means that the agricultural route for disposal needs to be protected by maintaining, or where possible increasing, existing levels of biosolids uptake by farmers. However, this presents wastewater companies with a number of challenges, such as those indicated in earlier studies (e.g. Sommers, 1997; Bowden and Hann, 1997), which combine to restrain the agricultural route as well as the opportunities to increase recycling targets in the longer term. These challenges can be overcome by developing sustainable wastewater treatment processes and sludge management practices. In particular, the improvement of biosolids quality can significantly contribute to minimise environmental concerns and secure the agricultural route (Davis, 2007). The focus on product quality, needed for increased acceptance of biosolids-based fertilisers, requires a cultural shift within wastewater management companies.

The need to increase agricultural production to sustain a growing population requires the development of sustainable technologies to ensure that food supply is not affected (Zeigler and Mohanty, 2010; McAllister et al., 2012). In the UK, some of the challenges associated with food security, sustainability and health are being addressed following the launch of the Food Strategy 2030 (Cabinet Office, 2008). Dawson and Hilton (2011) recognised that increased food production will bring about increased demand for mineral fertilisers. A more stable fertiliser demand may be achievable with improved efficiency of nutrient management from organic materials recycled to land combined with increased levels of recycling of these materials. McAllister et al. (2012) highlighted that a key requirement is to engineer nutrient use-efficient crops with particular regards to nitrogen which has a relatively low (range of 30% to 50%) use efficiency (Garnett et al., 2009).

Fischer et al. (2009) acknowledged the influence that input efficiency has on determining the cost of production of food crops while prices of non-renewables resources are also of great concern. There is a synergism amongst sustainable technologies which enable achieving not only greater yields but also greater resource efficiency (Fischer et al., 2009). Technology exists for the production of organomineral fertilisers (OMF) which can be obtained by coating biosolids granules with urea (46% N) and potash (60% K_2O) to provide a balanced compound fertiliser with suitable physical characteristics (Antille, 2011; Antille et al. 2013a). This product concept appears to be a sustainable approach to recycling biosolids to agriculture which aims to increase current levels of uptake by farmers offering an enhanced organic-based fertiliser material. An advantage of the coating technology is that it enables the concentration of nutrients in the OMF to be adjusted to meet specific soil and crop requirements. The development of such product requires evaluation at the field-scale to determine if the perceived agronomic, environmental and economic benefits can be effectively delivered.

The aim of this work was to assess the agronomic efficiency of two organomineral fertilisers (OMF) which were applied to a grass crop (*Lolium perenne* L) in a field-scale trial during 2009 and 2010. The OMF are referred to as OMF_{10} and OMF_{15} and have $N:P_2O_5:K_2O$ compositions 15:4:4 and 10:4:4 respectively (Antille, 2011; Antille et al., 2013a). The core of the granules (biosolids) releases nutrients more slowly compared with the mineral fraction (urea and potash) (Antille et al., 2012). The specific objectives of this study were to: (1) investigate total dry matter yield (DMY) and yield-to-nitrogen response curves to determine optimum OMF-N application rates, and (2) investigate changes in the overall fertility status of the soil with particular regards to potential build-up of soil P. It was hypothesised that: (1) DMY of the grass crop amended with OMF would be comparable to that of urea but higher than biosolids-treated crop, and (2) soil P levels would not change significantly as a result of OMF application and therefore soil P Index would remain close to constant. The results reported in this study aided the development of a set of practical recommendations concerning the use of OMF in grass crops. The conversion of biosolids into nutrient-balanced organomineral fertilisers addresses an important issue regarding input use efficiency in agriculture. It offers an opportunity for improved resource management to deliver some of the agronomic, economic and environmental benefits associated with recycling.

Materials and Methods

Experimental site

An experimental site was established at Cranfield University Silsoe (52°00'19" N, 0°25'36" W) located in Bedfordshire, England, in February 2009. The site had been occupied by a first (2006-2007) and a second (2007-2008) winter wheat (*Triticum aestivum* L) crops prior to the start of the experiment. The meteorological records for the site are shown in Figure 1 (Met Office, 2010). The soil type within the field is a *Cottenham series* sandy loam (King, 1969) which has 67% sand, 13% clay and 20% silt (Antille et al., 2012). The soil is well drained with a gentle slope (<1%). Field capacity determined at 0.05 bar reported a moisture content equivalent to 26.6% (w w^{-1}) (Antille, et al., 2012, 2013b). The mean annual rainfall recorded for the period 2009 to 2010 was 505 mm, about 15% lower compared to historic records (1971 to 2000) (Met Office, 2010). Air temperatures in the spring and summer of 2009 and 2010 were above the historic average. Smith and Trafford (1976) reported that Area 28 (Cambridgeshire and Bedfordshire) is characterised by a mean excess winter rain of 130 mm which allows the soil to return to field capacity around 10 December. This soil condition ends around 27 March but usually not later than 19 April. Mean soil moisture deficits of up to 85 mm and 103 mm typically occur at the end of June and at the end of July respectively (Smith and Trafford, 1976).

The experimental site was marked out to comprise 60 plots (plot dimensions: 2 m × 5 m) which were georeferenced to facilitate their re-positioning in subsequent years.

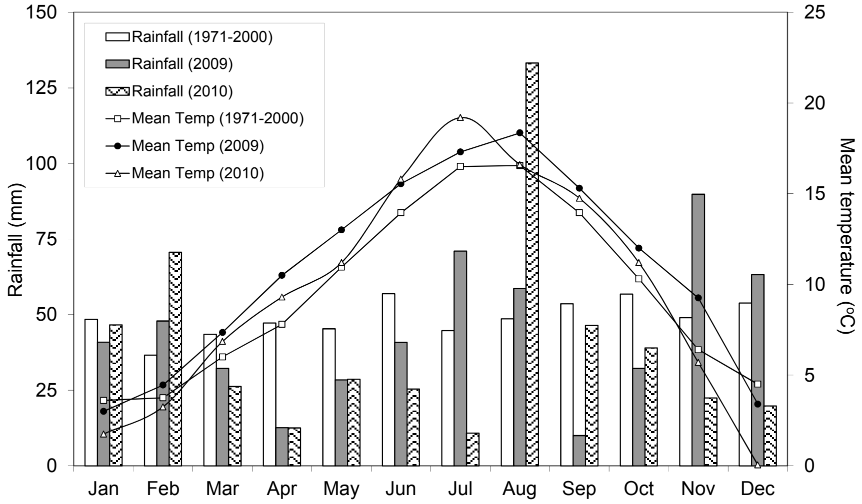

Figure 1: Rainfall and temperature records for Silsoe, Bedfordshire, UK (Met Office, 2010).

Grass crop

The grass crop was drilled on 30 March 2009 at a rate of 1.5 kg of seeds per ha and emergence recorded on 11 April 2009. A commercially available grass mix was used which consisted of 15% Molisto, 30% Gandalf, 30% Premium and 25% Fornax, all perennial ryegrass (*Lolium perenne* L). Broadleaves weeds were chemically controlled in post-emergence with a conventional herbicide following standard farm practices. The grass was harvested manually using a 0.5 m^2 quadrate which was placed approximately in the centre of the plot and the grass cut at 20 mm above the soil surface three times in 2009 (14 July, 25 August and 21 October) and two times in 2010 (17 April and 20 June). The harvested plant material was oven-dried at 60 degrees Celsius for 48 hours (MAFF, 1986) for determination of dry matter yield (DMY) which is reported in kg of dry matter (DM) per hectare. After each harvest, the entire experimental site was mechanically cut to about the same height (20 mm) to ensure that re-growth of the grass sward was uniform both in- and between-plots.

Yield-to-nitrogen response curves were examined by applying non-linear regression analyses (Sparrow, 1979). Quadratic functions (Equation (1)) were fitted to the data from which the maximum (Equation (2)) and the optimum (Equation (3)) dry matter yields were derived (Morrison et al., 1980).

$$y = a + bx - cx^2 \quad \textbf{(1)}$$

Where: *a*, *b* and *c* are regression coefficients, '*x*' is the nitrogen application rate and '*y*' is dry matter yield (DMY).

$$DMY_{\max}\left(\frac{dy}{dx}=0\right) \tag{2}$$

$$DMY_{10}\left(\frac{dy}{dx}=10\right) \tag{3}$$

Where: DMY_{max} and DMY_{10} are the maximum and the optimum dry matter yields (kg ha^{-1}) respectively. DMY_{max} is equivalent to the potential harvestable yield given the climatic and soil conditions, and subjected to the particular crop and fertiliser management practices (Morrison et al., 1980). DMY_{10} is the yield at which the response of the grass crop equates to 10 kg of DM per kg of N added. The nitrogen application rates (kg ha^{-1}) required for DMY_{max} and DMY_{10} are N_{max} and N_{10} respectively.

The agronomic efficiency of the N applied with the fertilisers (Equation (4)) was obtained using the difference method (Cassman et al., 1998; Johnston and Poulton, 2009). This parameter was calculated for the optimum dry matter yield (DMY_{10}) and the corresponding N application rate (N_{10}), and it is reported in kg of DM per kg of N.

$$Agronomic\ efficiency=\frac{DMY_{10}-DMY_{Control}}{N_{10}} \tag{4}$$

Where: $DMY_{Control}$ is the mean dry matter yield corresponding to the unfertilised control.

Fertiliser treatments

The experiment was subjected to the following treatments: two organomineral fertilisers (OMF), referred to as OMF_{15} (15:4:4) and OMF_{10} (10:4:4) (Antille, 2011; Antille et al., 2013a), were compared with a mineral fertiliser (urea, 46% N), and biosolids granules; the latter material had the following $N:P_2O_5:K_2O$ compositions: 4:6.6:0.1 and 5.5:4.3:0.2 for the batches corresponding to 2009 and 2010 respectively (Antille, 2011; Antille et al., 2013a). The fertilisers materials were hand-applied in a single dressing at rates ranging from 0 (control) to 250 kg ha^{-1} of N at regular increments of 50 kg ha^{-1} of N. There were two fertiliser applications which were conducted on 10 June 2009 and 18 April 2010 respectively. In 2010, the fertiliser application was conducted after the first cut of the grass to assess residual effects of OMF-N and biosolids-N on DMY up to this cut. This was justified given the relatively slow mineralisation rate of the organic-N fraction contained in OMF and biosolids granules (Antille et al., 2012). Under the UK conditions, mineralisation of biosolids-N and organic OMF-N is likely to continue well after the harvest of winter cereal crops when these materials are applied in early spring (Antille et al., 2012). Therefore, N carried over into the autumn and winter, if not lost by leaching or gaseous evolution, can influence DMY levels in the first cut the following year which needed to be assessed.

Soil analyses

Soil was sampled to a depth of 150 mm (DEFRA, 2010) and analysed using standard laboratory techniques. Soil sampling was conducted prior to the start of the experiment to determine background levels and routinely thereafter. The following analyses were conducted: total soil N (BS EN 13654-2, 2001), soil extractable P (Olsen et al., 1954; BS 7755 Section 3.6, 1995), soil exchangeable K (MAFF, 1986 Method No.: 63), soil pH (MAFF, 1986 Method No.: 32), soil organic matter (SOM) (MAFF, 1986 Method No.: 56), and soil mineral N (SMN) (MAFF, 1986 Method No.: 53). For soil exchangeable K, analyses were conducted for the control (zero-fertiliser) and the treatments that received 150 and 250 kg ha^{-1} of N. Analyses of soil extractable P and exchangeable K enabled examining changes in soil P and K Indexes respectively that occurred as a result of the fertiliser treatment. Soil P and K Indexes are defined in DEFRA (2010) and analytical values are expressed in mg L^{-1}. A soil bulk density value of 1.34 g cm^{-3} (Antille et al., 2012) was used to convert from mg L^{-1} to mg kg^{-1} (Johnston, 1975).

Statistical analyses

Statistical analyses were undertaken using GenStat 14th Edition. For dry matter yield (DMY), analyses involved ANOVA and least significant differences to compare the means with a probability level of 5% (LSD 5% level). For the measured soil chemical properties analyses involved repeated measurement of analysis of variance (5% level) which enabled factoring in the effect of the time. The experiment used a completely randomised design and all treatments were replicated three times (n=3) except for the controls (zero-fertiliser) and the plots treated with 250 kg ha^{-1} of N which were replicated four (n=4) and two (n=2) times respectively. This arrangement enabled fitting all plots within the designated experimental area and minimising the interference with the surrounding commercial crop in the field.

Results and Discussion

Dry matter yield and crop responses

Figure 2 shows dry matter yields (DMY) of the grass crop as affected by the fertiliser treatment in 2009 and 2010 respectively. In both years, there were significant differences in total (annual) DMY between the control and the treatments ($P<0.001$). The differences in DMY were significant with respect to the fertiliser type and the N application rate (P-values <0.001). The interaction fertiliser type × N application rate was not significant (P-values >0.05). On average across all treatments, the application of fertiliser increased DMY by about 80% in 2009 and approximately three times in 2010 compared with the controls. There was a positive response of DMY to the concentration of N in the fertiliser material; in particular, the concentration of readily available N. The first cut conducted in 2010 resulted in DMY levels in the range of 680 to 920 kg ha^{-1} of DM across all treatments which were not significantly different for an LSD value (5% level) of 388 kg ha^{-1} of DM. These results confirmed that the residual effect of the fertiliser applied in the previous year was relatively small and of similar magnitude across all treatments including the control. Hence, it is possible to suggest that losses of N via leaching or gaseous evolution had occurred following the third cut in 2009.

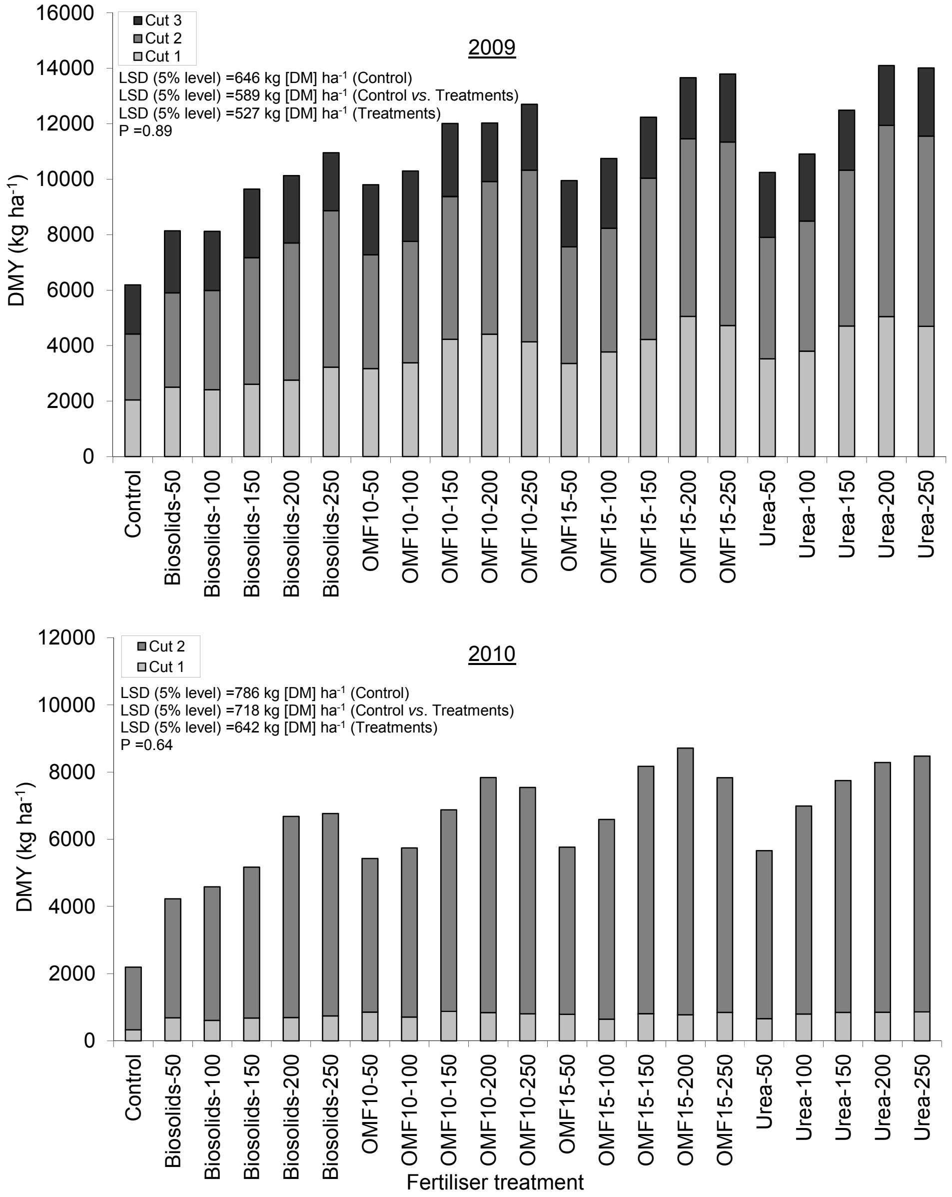

Figure 2: Dry matter yield (DMY) of the grass crop as affected by the fertiliser treatment in 2009 (*top*) and 2010 (*bottom*). The '*x*' axis shows the fertiliser type followed by the corresponding N application rate in kg per ha. Use n=4 (control) and n=3 (treatments) except when N=250 kg ha^{-1}, n=2.

Dry matter yield (DMY)

The functions used to describe the responses of the grass crop to the application of N showed acceptable fits to quadratic models, and the terms derived from these responses produced reasonable solutions (Table 1). Linear relationships were also possible since the estimates of parameters were significant (*p*-values <0.05) for the linear term in all cases. The responses of the grass crop to the application of biosolids did not produce a significant effect for the square term of the quadratic function which was observed in both years (*p*-values >0.05). Hence, the dry matter yield-to-nitrogen response curve for biosolids may be better explained by a linear function instead.

However, since the coefficients of the square term were negative, there was an indication that under the prevailing experimental conditions, DMY started to decline above certain level of N fertilisation. Therefore, the use quadratic functions to describe these responses may be justified which also enabled deriving the maximum (DMY_{max}) and the optimum dry matter yields (DMY_{10}) respectively.

The responses to the application of OMF_{10}, OMF_{15} and urea showed average increments in DM (range of 21 to 31 kg DM kg^{-1} N) which were within the range (from 14 to 29 kg DM kg^{-1} N) reported by Morrison et al. (1980) but exceeded those encountered by McFeely and MacCarthy (1981), and O'Donovan et al. (2004) (range of 5 to 17 kg DM kg^{-1} N). As highlighted for DMY, the responses were related to the concentration of readily available N in the fertiliser. Biosolids showed average increments in DM per additional unit of N which were between 16% and 30% lower than OMF or urea. Differences between-fertilisers were smaller in 2010 which responded to the combined effect of drier soil conditions in the early part of the spring (Figure 1) and the surface application of the fertilisers. This effect was observed despite that the timing of fertiliser application matched, approximately, the expected peak of growth of the grass crop which under the UK conditions typically occurs around May (Orr et al., 1988). The relatively dry and warm conditions recorded in April 2010 (Figure 1) support the possibility of N losses by volatilisation of NH_3 after the fertiliser application. For urea-containing fertilisers, these losses are enhanced at higher N application rates or with increased temperature (range of 10° to 30°C) (Watson et al., 1990).

The values of N_{max} obtained for biosolids granules (Table 1) should be treated with caution as they resulted from extrapolating data that falls outside the range of N application rates used in this study i.e. from 0 to 250 kg ha^{-1} of N. These N_{max} values however reflect the linearity of the responses of the grass treated with biosolids granules. In 2010, the grass treated with OMF_{15} marginally outperformed that treated with urea but the differences between the two fertiliser sources were not significant (LSD 5% level =525 kg DM ha^{-1}). The same was observed for the other parameters derived from the response curves as OMF_{15}-treated grass required slightly less N for both maximum (DMY_{max}) and optimum (DMY_{10}) yields. This was due to weather conditions recorded in the early part of the spring in 2010 (Figure 1); especially, the lack of rainfall during April which accounted for a total of 8.2 mm (Met Office, 2010).

The N10 values showed in Table 1 indicate the N application rates above which the response of the grass crop is less than 10 kg ha-1 of dry matter. This value is considered to be an adequate lower limit of response from the agronomic and environmental perspectives (Morrison et al., 1980). For all fertiliser types, the calculated values of N10 were approximately within the range of N application rates recommended for grass (cut) in RB209 (DEFRA, 2010) in situations with moderate to high soil N supply. These N10 values are also in close agreement with those obtained by Morrison et al. (1980) (range of 183 to 300 kg ha-1 of N) for more than 20 experimental sites scattered across England and Wales.

Table 1: Parameters derived from the response of the grass crop to the application of fertiliser-N in 2009 and 2010. Mean DMY is annual dry matter yield divided by the number of cuts in the corresponding year across all N application rates, and *SD* is the standard deviation. For mean DMY, different letters indicate values that are significantly different at a 95% confidence interval.

Treatment	2009									
Parameter	Mean DMY	*SD*	Response	*P*-value	R^2	DMY_{max}	N_{max}	DMY_{10}	N_{10}	Agronomic efficiency
Unit	kg ha^{-1}	kg ha^{-1}	---	---	---	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg [DM] kg^{-1} [N]
Control	6188^a	126	---	---	---	---	---	---	---	---
Biosolids	9285^b	1389	$y = 6406 + 24.6x - 0.03x^2$	<0.001	0.74	11986	455	11060	270	18.0
OMF_{10}	11270^c	1330	$y = 6576 + 53.8x - 0.12x^2$	<0.001	0.87	12460	219	12255	180	33.7
OMF_{15}	11958^d	1643	$y = 6547 + 56.9x - 0.11x^2$	<0.001	0.94	13798	255	13574	210	35.2
Urea	12230^d	1778	$y = 6586 + 60x - 0.12x^2$	<0.001	0.89	14027	248	13820	207	36.9
Treatment	2010									
Parameter	Mean DMY	*SD*	Response	*P*-value	R^2	DMY_{max}	N_{max}	DMY_{10}	N_{10}	Agronomic efficiency
Unit	kg ha^{-1}	kg ha^{-1}	---	---	---	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg [DM] kg^{-1} [N]
Control	2192^a	204	---	---	---	---	---	---	---	---
Biosolids	5394^b	1287	$y = 2435 + 26.6x - 0.04x^2$	<0.001	0.78	7266	364	6581	227	14.1
OMF_{10}	6624^c	1080	$y = 2532 + 46.9x - 0.11x^2$	<0.001	0.90	7651	218	7418	172	25.8
OMF_{15}	7385^d	1266	$y = 2396 + 63.6x - 0.17x^2$	<0.001	0.92	8500	192	8348	162	32.1
Urea	7357^d	1240	$y = 2523 + 58.4x - 0.14x^2$	<0.001	0.90	8477	204	8302	170	30.4

In situations where soil N supply is low, or where more than three cuts are performed during the main growing season (April to September), the use of a straight N source may be recommended after the second cut. The application of N should follow the general guidelines given in RB209 (DEFRA, 2010). Therefore, N application rates for individual cuts should not exceed 120 kg ha^{-1}; this is an important consideration given that OMF contains urea which is prone to volatilisation at high N application rates (Watson et al., 1990). For the first cut, which is typically the one that requires the highest N dressing (e.g. 120 to 150 kg ha^{-1} of N), apply about 30% to 40% between middle of February and early March with the balance in late March to early April allowing a minimum of 6 weeks before the cut. For subsequent cuts, N should be applied immediately after the previous cut but because the N rates are usually lower than 120 kg ha^{-1}, the full dressing may be applied. Because of the characteristics patterns of growth of grass swards under the UK conditions (Orr et al., 1988), this fertilisation strategy will maximise the response of the grass to the application of fertiliser-N, including OMF-N, and will minimise the opportunities for N losses to the environment (DEFRA, 2010; Antille et al., 2013a). In 2009, the recommendations regarding the timing of fertiliser application could not be strictly followed because it was the year of grass establishment and emergence was recorded on 11 April.

For OMF_{10} and OMF_{15}, an average input of about $0.8\times N_{max}$ yielded $0.98\times DMY_{max}$ which was similar to that of urea whereas for biosolids, a yield of $0.92\times DMY_{max}$ required an input of $0.61\times N_{max}$ but DMY was significantly lower. The agronomic efficiencies of the fertilisers applied reflect an improved performance of the grass crop treated with OMF_{10}, OMF_{15} and urea relative to that of biosolids granules as well as differences in their relative effectiveness between-years. In the drier year (2010), the efficiency of biosolids-N was affected by lower microbial activity which reduced the mineralisation rate of organic-N in the material. For OMF and urea water shortages translated into greater N losses by volatilisation of NH_3, hence, N availability to the grass crop and reduced N uptake (Watson et al., 1990) which is reflected in the relatively lower agronomic efficiencies obtained in the second year.

Nitrogen in soil

The controls did not show significant differences in total N in soil compared with the treatments at the end of the experiment ($P=0.06$). However, there were significant differences ($P<0.001$) both in the control plots and the treatments compared with the initial levels of total N in soil recorded at the start of the experiment (Figure 3). The effects of the fertiliser type or N application rate on total N in soil were not significant (P-values >0.05) which suggested that there was an effect of the grass crop that masked the differences between the control and the treatments.

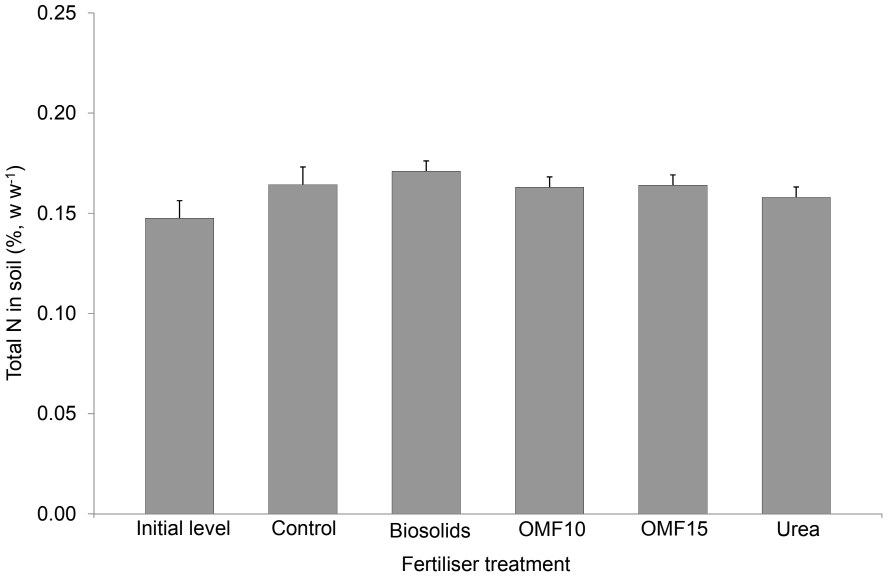

Figure 3: Mean total N in soil over the range of fertiliser application rates used in the experiment. The initial level corresponds to the baseline level prior to the start of the experiment. Use n=14 except for initial level and control n=3; P=0.06 (control *vs*. treatments), P=0.91 (treatments). The error bars show the LSD value at 5% level.

The increase in total N in the control plots compared with the initial level is attributed to restricted crop growth and therefore reduced N uptake in the absence of N fertilisation, and the effect of mulching which returned organic matter to the soil after each cut. Despite that there was no effect of fertiliser type (P>0.05), the application of biosolids granules increased total N levels marginally after two years compared to the control and the other treatments (Figure 3). These changes should be monitored if routine applications of biosolids are to be implemented as they can affect soil N supply in subsequent years, hence, fertiliser N recommendations.

Sylvester-Bradley (1993) suggested that there is scope for reducing N fertilisation if soil N supply could be accurately predicted for the main growing season. However, its estimation based on soil mineral N (SMN) does not appear to be a reliable approach in this study since the overall differences between the control and the treatments were not significant (P=0.21). There was an effect of the fertiliser type (P=0.02) which was due to marginally higher SMN levels recorded in urea-treated plots compared with the other treatments. However, SMN values were generally low across all fertiliser treatments and rarely exceeding 5 mg kg^{-1} as determined annually before the fertiliser application and after the last cut of the grass crop. The ample period of growth of the grass crop, hence N uptake, combined with a relatively slow mineralisation rate of organic-N in OMF and biosolids (Antille et al., 2012) explain the results obtained in the analyses.

Soil extractable phosphorus

The control and the treatments reported soil P Index 5 which equates to Olsen's P in the range of 71 to 100 mg L^{-1} (DEFRA, 2010). Figure 4 shows that overall, there were no significant differences in soil extractable P between the control and the treatments (P=0.92) but there was a significant effect of the fertiliser type (P=0.01). This effect was due to the relatively higher soil extractable P value recorded in biosolids-treated plots compared with those treated with OMF$_{10}$, OMF$_{15}$ and urea. The application of OMF did not change soil extractable P levels significantly compared with the unfertilised control plots; therefore, soil P Index remained unchanged.

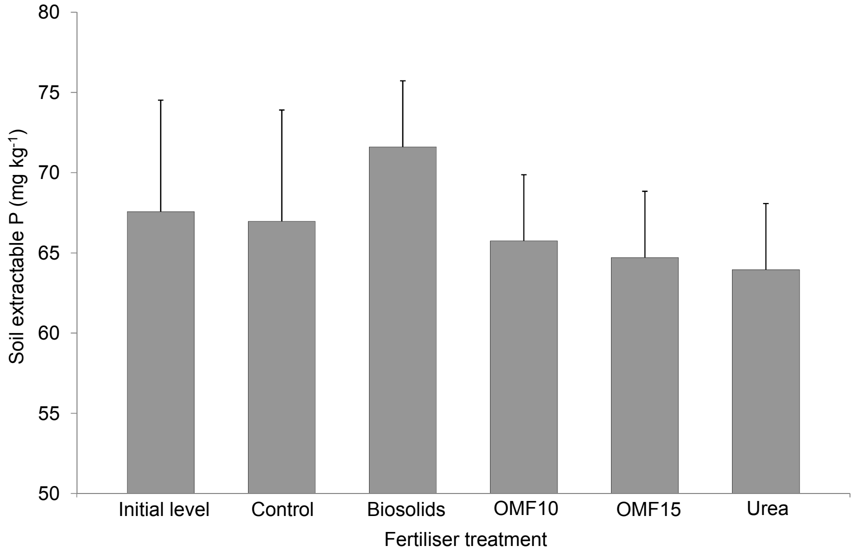

Figure 4: Mean soil extractable P over the range of fertiliser application rates used in the experiment. The initial level corresponds to the baseline level prior to the start of the experiment. Use n=14 except for initial level and control n=3; P=0.92 (control *vs*. treatments), P=0.01 (treatments). The error bars show the LSD value at 5% level.

Despite that the differences observed between-fertiliser treatments were small; the results showed that continuous application of biosolids granules will tend to build-up soil extractable P levels while the absence of P fertilisation in urea-treated grass will have the opposite effect. On the contrary, the application of OMF_{10} and OMF_{15} maintained soil P status close to constant which therefore supports the reasons for the proposed OMF formulations (Antille, 2011; Antille et al., 2013a). The importance of these results strives in the need to ensure that soil extractable P is not increased in those soils which have satisfactory P levels, as defined in DEFRA (2010), but that their overall fertility is maintained.

The results obtained with biosolids reflected the issue of potential build-up of soil P when materials with low N:P ratio (≈1) are applied based on the N requirements of the crop. They also highlight one of the limitations being faced by wastewater operators in the NW of England regarding the application of biosolids in agricultural land which has satisfactory soil P Indexes (Skinner and Todd, 1998; DEFRA, 2010). The conversion of sludge into balanced organomineral fertilisers has therefore potential to address this issue and increase recycling targets in areas close to production.

The small decline in soil extractable P in urea-treated plots also responded to the relatively higher DMY obtained with this fertiliser (Table 1) which resulted in enhanced P removal. In soils with adequate P and K Indexes (DEFRA, 2010), avoidance of P and K fertilisation may not affect DMY of grass crops in the short-term (Johnston et al., 2001). The long-term experiments at Rothamsted in the UK (Johnston, 1997) showed that continuous omission of P and K application causes reduction in crop yield when the available soil P and K reserves have declined below a critical level appropriate for the soil and crop system (Johnston et al., 2001). Below this level, and due to nutrient interactions, N use efficiency in grassland soils is significantly affected which has adverse effects both from the economic and environmental perspectives (Johnston et al., 2001; Johnston and Milford, 2007; Dawson, 2011). Since the availability of biosolids-N is low (Antille et al., 2012), DMY and P uptake in biosolids-treated crop were restricted by N supply which contributed to maintain relatively higher concentrations of P in the soil solution compared with the other treatments.

The application of OMF-N at rates equivalent to N_{10} should not increase soil P Index as they fall below the maximum N rate tasted in this study which did not result in significant changes in soil P status. On the contrary, the application of OMF at the optimum rate will replenish, approximately, P off-take by the crop thereby maintaining soil P levels close to constant over time. Previous studies with OMF under controlled glasshouse conditions (Antille, 2011) showed that P uptake in OMF-treated grass was greater ($P<0.05$) than that of biosolids granules. The enhanced uptake of P with the use of a fertiliser material with higher readily available N content was due to the positive interaction that exists between the two plant nutrients (Mouat and Nes, 1983). Reduced P uptake in biosolids-treated grass led to a significant change (increase) in soil extractable P after three years (Antille, 2011). For OMF-treated grass, the same study showed that soil extractable P levels were not modified significantly ($P>0.05$) which agrees with the results presented in this article. This occurred despite of the relatively low bioavailability of P contained in the OMF (Antille et al., 2012). The application of P with OMF replenishes the less readily available and the very slowly available soil P pools which overtime are released to the readily available pool and the soil solution i.e. the two fractions measured in routine soil analyses (Johnston and Syers, 2006). This process enables restoring soil extractable P levels that had been temporarily diminished as a result of P uptake by the crop.

Analyses of soil pH showed that there were no significant differences between the control and the treatments, and that there was no effect of the fertiliser type, the application rate or the interaction fertiliser rate × fertiliser type (P-values >0.05). Therefore, changes in soil extractable P cannot be explained by differences in soil pH between fertiliser treatments. Soil organic matter was also measured but there were no significant differences between the control and the treatments ($P=0.82$).

Soil exchangeable potassium

Overall, there were significant differences in soil exchangeable K between the control and the treatments ($P=0.04$), and there was a significant effect of the fertiliser type ($P=0.02$). All fertiliser treatments showed a small decline in soil K Index from 3, as recorded for the control at the start of the experiment, to 2+ (DEFRA, 2010). The decline in soil exchangeable K occurred to a greater extent in urea-treated plots which showed a relatively lower value (153 mg kg^{-1}) compared with the control (201 mg kg^{-1}). OMF_{10} and OMF_{15} showed intermediate levels of soil exchangeable K (166 and 168 mg kg^{-1} respectively) between the control and the plots treated with biosolids granules (180 mg kg^{-1}). There was no effect of the fertiliser application rate ($P=0.06$) but soil exchangeable K decreased approximately 10% more in plots that received 250 kg ha^{-1} of N compared to those at 150 kg ha^{-1} of N. These results explain differences in K uptake by the grass crop as a result of the fertiliser treatment and reflect the positive interaction that exists between nitrogen and potassium (Johnston and Milford, 2007). Higher N application rate combined with increased N availability in the fertiliser applied (e.g. urea at 250 kg ha^{-1} of N) enhanced biomass production and K uptake; hence, soil exchangeable K recorded a lower value in the analyses. The above is possible because of the satisfactory soil K Index observed at the start of the experiment.

For OMF-treated grass, the supply of K with the fertiliser offset to a greater extent than urea, the decline in soil exchangeable K despite the relatively high DMY levels observed (Table 1). The addition of K with biosolids was negligible given its low concentration in the material (Antille, 2011). However, DMY was restricted by the availability of N contained in the biosolids; hence, K uptake was reduced and the levels detected in the soil analyses remained closer to the initial values. The same mechanism of reduced uptake holds true for the unfertilised (control) grass crop. The trends observed in soil exchangeable K levels that resulted from the fertiliser treatment may be monitored in the longer-term.

Because the efficiency of applied fertiliser N is affected by the availability of soil K, this becomes an important consideration in situations where crop management practices do not include regular applications of K fertilisers (Johnston et al., 2001).

Conclusions

1. The proposed OMF_{10} and OMF_{15} formulations are suitable for application in grass crops. The slightly lower DMY levels obtained on average with OMF compared with urea were influenced by relatively dry conditions observed in the second year of the experiment which affected the mineralisation rate of organic-N in OMF. However, agronomic efficiency calculations showed a significantly improved performance of the grass crop treated with OMF compared with biosolids granules, and comparable to that obtained with straight N. Therefore, the efficiency of nutrient uptake from applied OMF is comparable to that of a mineral N fertiliser despite the organic nature of the material.
2. The response curves to the application of OMF-N showed average increments in dry matter yield which were approximately within the range reported in the literature for straight N fertilisers. The optimum N application rates with OMF were within 10% difference compared with urea, and consistently lower than biosolids. This has implications from the economic and environmental perspectives in regards to the cost of field spreading and N load on the environment.
3. Based on the results of the experiment conducted, the article outlines a set of general guidelines regarding the timing of OMF application in relation to the recommended N rates and the characteristic patterns of growth of grass crops under the UK conditions. The proposed fertilisation strategy aims to maximise the response of the grass to the application of fertiliser-N, including OMF-N, and therefore to minimise the opportunities for N losses to the environment.
4. The application of OMF did not result in significant changes in soil extractable P levels; hence, soil P Index was not affected which confirmed the hypothesis formulated prior to this study. This result demonstrated the benefits of OMF compared with biosolids when the materials are applied on soils which have satisfactory P levels and therefore the potential that this product has to meet long-term recycling targets in areas close to production.

Acknowledgements

This research received funding from the European Union Seventh Framework Programme (FP7-ENV.2010.3.1.1-2 ENV, Grant agreement No.: 265269) and from United Utilities Group PLC. The article represents the opinion of the authors and does not necessarily represent the view of the European Union or United Utilities Group PLC. The authors are grateful to The Engineering and Physical Science Research Council and Cranfield University for financial and operational support. Help received from S.F. Tyrrel, P. Bellamy, R.J. Walker and the staff at the Soil and Water Laboratory (Cranfield University) is appreciated. The University of Southern Queensland through the NCEA provided financial support to attend the 2013 ASABE Annual International Meeting.

References

Antille, D.L., 2011. Formulation, utilisation and evaluation of organomineral fertilisers. *Engineering Doctorate Thesis*. School of Applied Science, Cranfield University, UK. 572 pp.

Antille, D.L.; Ansorge, D.; Dresser, M.L.; Godwin, R.J., 2013b. Soil displacement and soil bulk density changes as affected by tire size. *Transactions of the ASABE* 56 (5). (In press).

Antille, D.L.; Sakrabani, R.; Godwin, R.J., 2012. Nitrogen and phosphorus availability following topsoil application of organomineral fertilisers (OMF). ASABE Paper No.: 12-1340682, St. Joseph, Mich.: ASABE.

Antille, D.L.; Sakrabani, R.; Tyrrel, S.F.; Le, M.S.; Godwin, R.J., 2013a. Characterisation of organomineral fertilisers derived from nutrient-enriched biosolids granules. *Applied and Environmental Soil Sci*., Article 694597. (In press).

Bowden, W.; Hann, M.J., 1997. The availability of nitrogen following digested sludge incorporation in arable land. *Nut. Cycling in Agroecosyst.* 47 (2): 167-172.

BS 7755 Section 3.6, 1995; British Standard 7755 Section 3.6, 1995. Determination of phosphorus: spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution. Equivalent to ISO 11263:1994. The British Standards Institution, London.

BS EN 13654-2, 2001; British Standards EN, 2001. Soil improvers and growing media. Determination of nitrogen. Dumas Method. Equivalent to ISO 5725:1994. The British Standards Institution, London.

Cabinet Office, 2008. Food matters – Towards a strategy for the 21st century. The Cabinet Office, London. Accessed 12 July 2013. http://webarchive.nationalarchives.gov.uk/+/http:/www.cabinetoffice.gov.uk/media/cabinecabinet/strategy/assets/food/food_matters1.pdf.

Cassman, K.G.; Peng, S.; Olk, D.C.; Ladha, J.K.; Reichardt, W.; Dobermann, A.; Singh, U., 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Res*. 56 (1-2): 7-38.

CEC, 1991; Council of the European Communities, 1991. Council Directive concerning the protection of water against pollution caused by nitrates from agricultural sources. Council Directive of 31 December 1991 (91/676/EEC). *Official J. of the European Comm*. L375: 1-5.

CEC, 1999; Council of the European Communities, 1999. Council Directive 99/31/EC of 26 April 1999 on the landfill of waste. *Official J. of the European Communities* L182: 1-19.

Davis, R.D., 2007. The impact of EU and UK environmental pressures on the future of sludge treatment and disposal. *Water and Environ. J*. 10 (1): 65-69.

Dawson, C.J., 2011. Phosphate and potash – reconsidering their importance and use. *J. of the Royal Agric. Soc. of England* 172: 1-9.

Dawson, C.J; Hilton, J., 2011. Fertiliser availability in a resource-limited world: production and recycling of nitrogen and phosphorus. *Food Policy* 36 (1): 14-22.

DEFRA, 2002; Department for Environment, Food, and Rural Affairs, 2002. Sewage treatment in the UK: UK implementation of the EC Urban Waste Water Treatment Directive. PB 6655. DEFRA Publications, London.

DEFRA, 2010; Department for Environment, Food and Rural Affairs, 2010. Fertiliser manual (RB209). 8th Edition. The Stationery Office, London.

EC, 2012; European Commission, 2012. Environment: sewage sludge. Accessed 12 July 2013. http://ec.europa.eu/environment/waste/sludge/index.htm.

Edge, D., 1999. Perspectives for nutrient removal from sewage sludge and implications for sludge strategy. *Environ. Technology* 20 (7): 759-763.

Fischer, R.A.; Byerlee, D.; Edmeades, G.O., 2009. Can technology deliver on the yield challenge to 2050? FAO, Economic and Social Development Department. Expert Meeting on How to Feed the World in 2050 held in Rome on 24-26 June 2009. 24-26 pp.

Garnett, T.; Conn, V.; Kaiser, B.N., 2009. Root based approaches to improving nitrogen use efficiency in plants. *Plant Cell Environ*. 32 (9): 1272-1283.

GenStat Release 14.1 (14th Edition), 2011. Lawes Agricultural Trust, Rothamsted Experimental Station, Harpenden, UK. Registered to Cranfield University, UK.

Johnston, A.E., 1975. The Woburn Market Garden experiment, 1942-69. II: Effects of the treatments on soil pH, soil carbon, nitrogen, phosphorus and potassium. Rothamsted Experimental Station Report for 1974, 2: 102-131.

Johnston, A.E., 1997. The value of long-term field experiments in agricultural, ecological and environmental research. *Advances in Agronomy* 59: 291-333.

Johnston, A.E.; Milford, G.F.J., 2007. Potassium and nitrogen interactions in crop production. Proc. No.: 615. The Int. Fert. Soc., York, UK.

Johnston, A.E.; Poulton, P.R., 2009. Nitrogen in agriculture: an overview and definitions of nitrogen use efficiency. Proc. No.: 651. The Int. Fert. Soc., York, UK.

Johnston, A.E.; Poulton, P.R.; Dawson, C.J.; Crawley, M.J., 2001. Inputs of nutrients and lime for the maintenance of fertility of grasslands soils. Proc. No.: 486. The Int. Fert. Soc., York, UK.

Johnston, A.E.; Syers, J.K., 2006. Changes in understanding the behaviour of soil and fertiliser phosphorus: implications for their efficient use in agriculture. Proc. No.: 589. The Int. Fert. Soc., York, UK.

King, D.W., 1969. Soils of the Luton and Bedford Districts: a reconnaissance survey. The Soil Survey of England and Wales, Harpenden, UK.

MAFF, 1986; Ministry of Agriculture, Fisheries and Food, 1986. The analysis of agricultural materials. Reference Book 427. 3rd Edition. The Stationery Office, London.

McAllister, C.H.; Beatty, P.H.; Good, A.G., 2012. Engineering nitrogen use efficient crop plants: the current status. *Plant Biotechnology J.* 10 (9): 1011–1025.

McFeely, P.; MacCarthy, D., 1981. Effect of time on initial spring grazing and nitrogen use on pasture production. *Irish J. of Agric. Res*. 20: 137-146.

Met Office, 2010; Meteorological Office, 2010. Historic station data. Accessed 06 October 2010. http://www.metoffice.gov.uk/climate/uk/stationdata/.

Morrison, J.; Jackson, M.V.; Sparrow, P.E., 1980. The response of perennial ryegrass to fertilizer nitrogen in relation to climate and soil. Report of the joint ADAS/GRI Grassland Manuring Trial GM20. Grassland Research Institute Technical Report No.: 27. GRI, Hurley, Berkshire, UK.

Moseley, P.J.; Misselbrook, T.H.; Pain B.F.; Earl R.; Godwin R.J., 1998. The effect of injector tine design on odour and ammonia emissions following injection of bio-solids into arable cropping. *J. of Agric. Eng. Res*. 71: (4) 385-394.

Mouat, M.C.H.; Nes, P., 1983. Effect of the interaction of nitrogen and phosphorus on the growth of ryegrass. *New Zealand J. of Agric. Res*. 26 (3): 333-336.

O’Donovan, M.; Delaby, L.; Stakelum, G.; Dillon, P., 2004. Effect of autumn/spring nitrogen application date and level on dry matter production and nitrogen efficiency in perennial ryegrass swards. *Irish J. of Agric. and Food Res*. 43 (1): 31-41.

Olsen, S.R.; Cole, C.V.; Watanabe, F.S.; Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No.: 939.

Orr, R.J.; Parsons, A.J.; Treacher, T.T.; Penning, P.D., 1988. Seasonal patterns of grass production under cutting or continuous stocking management. *Grass and Forage Sci*. 43 (2): 199-207.

Petts, J., 1994. Incineration as a waste management option. *In*: Hester, R.E.; Harrison, R.M. (Eds.). Waste incineration and the environment. Royal Society of Chemistry, Cambridge, UK.

Skinner, R.J.; Todd, A.D., 1998. Twenty five years of monitoring pH and nutrient status of soils in England and Wales. *Soil Use and Management* 14 (3): 162-169.

Smith, L.P.; Trafford, B.D., 1976. Climate and drainage. Ministry of Agriculture, Fisheries and Food, Technical Bulletin No.: 34. The Stationery Office, London.

Sommers, L.E., 1997. Chemical composition of sewage sludges and analysis of their potential use as fertilizers. *J. of Environ. Quality* 6 (2): 225-232.

Sparrow, P.E., 1979. The comparison of five response curves for representing the relationship between the annual dry-matter, yield of grass herbage and fertilizer nitrogen. *J. of Agric. Sci*. 93 (3): 513-520.

Sylvester-Bradley, R., 1993. Scope for more efficient use of fertilizer nitrogen. *Soil Use and Management* 9 (3): 112-117.

Watson, C.J.; Stevens, R.J.; Garret, M.K.; McMurray, C.H., 1990. Efficiency and future potential of urea for temperate grassland. *Fert. Res*. 26 (1-3): 341-357.

Zeigler, R.S.; Mohanty, S., 2010. Support for international agricultural research: current status and future challenges. *New Biotechnol*. 27 (5): 565-572.