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Estimation of maximum biosolids and meat and bone meal application to a low P Index soil and a method to test for nutrient and metal losses

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Abstract

The aim of this study was to develop: (1) a method for the calculation of the maximum legal rate at which meat and bone meal (MBM) and biosolids should be applied to land, which took into account the soil P index, the dry solids and the nutrient and metal content of each material, and (2) a quick method to evaluate their impact, when applied at the estimated maximum and twice the maximum application rates, on the release of phosphorus (P) and metals to surface runoff. Three types of biosolids - lime stabilised (LS), anaerobically digested (AD) and thermally dried (TD) – and two types of MBM (low and high ash) were examined. The nutrient and metal losses were examined using a 1 L-capacity beaker, which contained an intact soil core. Treatments were applied at maximum and twice the maximum legal application rates and then overlain with 500 mL of water, which was stirred to simulate overland flow. At the maximum legal application rate, low ash MBM (1.14 mg L^{-1}) and TD biosolids (2.43 mg L^{-1}) had the highest losses of P. Thermally dried biosolids and LS biosolids exceeded maximum allowable concentrations (MAC) for manganese, but all treatments remained below the MAC for copper and iron, at the maximum legal application rate. Anaerobically digested biosolids, and high and low ash MBM would appear to have potential for landspreading, but these results are indicative only and should be verified at field-scale.

Keywords: Meat and bone meal; biosolids; land application; surface runoff; metals; dissolved reactive phosphorus.

1. Introduction

Biosolids are the by-product of urban wastewater treatment, whereas meat and bone meal (MBM) is derived through the processing of the residues from the slaughtering of farmyard animals. When spread on arable or grassland, and provided that they are treated to the approved standards, they may offer an excellent source of nutrients and metals required for plant and crop growth. They can be used as an aid in the development of a soil's physical and chemical characteristics. They increase water absorbency and tilth, and may reduce the possibility of soil erosion (Meyer et al. 2001). Land application of biosolids and MBM to agricultural land can be relatively inexpensive in countries such as the Republic of Ireland (hereafter referred to as Ireland) and the U.S.A, as such by-products are defined as wastes. An alternative, but costly, option in such countries is to pay tipping fees for their disposal (McFarland et al. 2007; Sonon and Gaskin 2009). For countries that acknowledge their nutrient replacement potential (e.g. the U.K), there is an associated cost for their usage.

1.1 Meat and Bone Meal

Initially across the European Union (EU), the application of MBM to land was prohibited, (European Commission 2000), but in recent years this stipulation has been relaxed and the application of MBM is now allowed provided certain criteria, detailed in Table 1, are adhered to (European Commission 2006; European Commission 2002). European Commission regulation No. 181 of 2006 (European Commission 2006) allows Member States to apply stricter national rules (European Commission 2000) and in Ireland, the land application of organic fertilisers composed of Category 2 and 3 MBM materials (Table 2) is prohibited (S.I. No. 253 of 2008). In 2010, 135,000 tonnes of MBM was produced from nine rendering plants approved by the Department of Agriculture, Fisheries and Food (DAFF) in Ireland (DAFF 2011) and as land application of MBM is not currently permitted, it is either incinerated, used in the cement industry, or used in the manufacture of fertiliser. As the world reserves of phosphate are diminishing and new reserves become more inaccessible, price increases will inevitably ensue (Cordell et al. 2009), thereby making MBM a more desirable alternative to synthetic fertilisers.

1.2 Biosolids

The amount of sewage sludge being applied to land in the EU has dramatically increased (Fig. 1). This is as a result of Directive 91/271/EEC (EEC 1991), which states that the sludge produced from wastewater treatment plants “shall be reused wherever appropriate” and the Landfill Directive, 1999/31/EC (EC 1999), which requires that, by 2014, the disposal of biodegradable municipal waste *via* landfill is to be reduced to 85 % of the total amount produced in 1995. Consequently, the land application of biosolids provides a sustainable and beneficial alternative to landfilling. Although Germany and the U.K. are two of the largest producers of sewage sludge in the EU, Ireland, the U.K. and Spain are at the forefront of EU countries in terms of the percentage of sludge reused on agricultural lands (Fig. 1).

In Ireland, the application rate of biosolids to land is governed by EU Directive 86/278/EEC (EEC 1986), and is enacted in the "Codes of Good Practice for the Use of Biosolids in Agriculture" (Fehily Timoney and Company 1999) (Table 1), which set out limits for metal application, and S.I. 610 of 2010, which sets out nutrient (P and N) limits for various crops grown in Ireland. These guidelines do not consider the relationship between biosolids application rate, nutrient availability, and surface runoff of nutrients, suspended sediment (SS) and metals. Generally, when applying biosolids based on these guidelines and depending on the nutrient and metal content of the biosolids, P becomes the limiting factor for application. In the U.S.A., the application of biosolids to land is governed by *The Standards for the Use or Disposal of Sewage Sludge* (U.S. EPA 1993), and is applied to land based on the nitrogen (N) requirement of the crop being grown and is not based on a soil test (McDonald and Wall 2011). Therefore, less land is required for the disposal of biosolids than in countries where it is spread based on P content. Evanylo (2006) suggests that when soil P poses a threat to water quality in the U.S.A., the application rate could be determined on the P needs of the crop. A consequence of excessive application rates could be nutrient losses where an application is followed by a rainfall event, or excessive heavy metals transfer from spreading lands along the export continuum to a waterbody with subsequent adverse effects to the environment (Navas et al. 1999).

Two knowledge gaps concerning the application of biosolids and MBM to soil exist: (1) the development of a simple method to determine their maximum legal application rate and (2) the development of a simple, quick and relatively realistic laboratory-based method to determine the impact of land application of biosolids and MBM on the release of P and metals to surface runoff. A novel test, wherein an intact soil, placed in a beaker, which has received a surface application of organic waste material and is then overlain with water, continuously stirred to simulate overland water flow may be used to give an indication of the potential impact of biosolids and MBM applications on surface water runoff of nutrients and metals.

Therefore, the aims of this study were to: (1) develop a simple, novel method to calculate the maximum legal application rate of biosolids and MBM to land (2) use a novel, quick, laboratory-based method to determine the impact of land applications of three types of biosolids (anaerobically digested (AD), thermally dried (TD) and lime stabilised (LS)) and two types of MBM (high ash and low ash content), applied at the maximum legal and double the maximum legal application rate, on P and heavy metal release.

2. Materials and Methods

2.1 Biosolids and MBM collection and characterisation

Three types of biosolids – AD, TD and LS - were collected from three wastewater treatment plants in Ireland. Two types of MBM samples, one with low ash content and one with high ash content, were collected from a slaughterhouse in the west of Ireland. The biosolids and MBM samples were stored in a cold room at a temperature of 10^{o}C prior to testing for P, nitrogen (N), and metal (cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury

(Hg), nickel (Ni) and zinc (Zn)) contents in accordance with standard methods (APHA 1995) (Table 3).

2.2 Soil Preparation and Analysis

The soil used in this study was collected from a dairy farm in Co. Galway, Ireland (ITM reference 552075, 717769). Cores with an internal diameter of 0.1 m and a depth of 0.12 m were used to collect undisturbed grassed soil samples from the site. The cores were pushed into the ground and were then carefully extruded from the soil so as not to disturb the soil contained within. Although no attempt was made to remove the grass from the surface of the soil cores, the grass was trimmed to a height of approximately 3 cm above the soil surface. The water content of the soil was approximately 27% and the intact cores were stored at approximately 10^{o}C before testing (normally < 2 d). Classification of the soil used in study is presented in Table 4. A 2:1 ratio of deionised water to soil was used to determine the soil pH (n=3). Soil samples (n=3), taken from the top 0.1 m from the same location, were air dried at 40^{o}C for 72 h, crushed to pass a 2 mm sieve and analysed for P using M3 extracting solution (Mehlich 1984) and Morgan's P (Pm; the national test used for the determination of plant available P in Ireland) using Morgan's extracting solution (Morgan 1941). The organic matter (OM) of the soil was determined by the loss of ignition (LOI) after BSI (1990).

2.3 Determination of maximum legal loading rate

In Ireland, a soil test P Index, which comprises a series of P ranges, four in total and based on the Pm content of the soil, describes the level of P saturation in a soil. A soil with a P Index of 1 (0-3 mg L^{-1} Pm for grassland) has a very low P content and therefore can have the highest amount of P spread on it, while a soil with a P Index of 4 (>8 mg L^{-1} Pm for grassland) has a very high P content and should not be spread with organic wastes or amended with synthetic fertilizers. The soil used in this study had a P Index of 1. The maximum legal application rate (in tonnes ha^{-1} y^{-1}) for each amendment used in the present study was determined based on the P index of the soil, the legal limits of the N, P and metal application (after Fehily Timoney and Company 1999; Table 1), the dry solids (DS) content, and nutrient and metal concentration of the amendment (either biosolids or MBM; Table 3). A flow chart of the methodology is presented in Fig. 2.

Both the biosolids and the MBM were applied at the maximum legal and double the maximum legal land application rate to be applied to a P index 1 soil, based on DS content of amendment (Table 5). In all cases, P proved to be the limiting factor of all the nutrients and heavy metals in terms of determining the legal application rate for each treatment.

2.4 Runoff test

The following treatments were carried out in triplicate (n=3): grassland only treatment (the study control); grassland receiving TD, LS and AD biosolids; and grassland receiving high ash and low ash-content MBM.

Intact soil cores (collection method detailed in Section 2.2), 0.04 to 0.05 m in depth, were placed in 1-L capacity Pyrex cylinders. The treatments were then applied to the soil (t=0 h) and left for a period of 24 h to allow the treatment to interact with the soil. After 24 h, the samples were then saturated by the gradual addition of deionised water over a 24-h period. This was conducted until slight ponding of water occurred on the soil surface. At t=48 h, 500 ml of deionised water was added to the breakers. A paddle was then lowered to mid-depth in the overlying water and rotated at 20 rpm for 30 h to simulate overland flow and at time intervals of 0.25, 0.5, 1, 2, 4, 8, 12, 24 and 30 h, 2.5 ml of water was removed at mid-depth of the overlying water, filtered through 0.45 μm filters and stored at 4^{o}C until testing (normally conducted within 1 d of collection). The samples were tested colorimetrically for dissolved reactive phosphorus (DRP) in accordance with the standard methods (APHA 1995) by a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). The mass release of DRP to the overlying water was calculated based on the concentration of the overlying water, the volume reduction due to sample withdrawal and the area of the exposed soil. At the end of each test, 15 ml of supernatant water was removed from each beaker and filtered through a 0.45-μm filter prior to testing for metal content (Cr, Cu, iron (Fe), manganese (Mn), Ni and Zn). Measurements of pH and dissolved oxygen (DO) were also taken at the 1, 8 and 30-h intervals and were measured using a pH probe (WTW SenTix 41 probe with a pH 330 meter, WTW, Germany) and a DO probe (WTW Oxi 315i meter with a CellOx 325 oxygen sensor, WTW, Germany), respectively.

2.5 Statistical Analysis

Two-sample t tests were used to determine the statistical difference in P release between P index 1 and double the P Index 1 application rates (at the 95 % confidence interval) for each of the treatments used (Minitab 16^{TM}; Minitab Inc., UK). It was also used to establish if, at a given loading rate, there was a difference in P release between the different treatments.

3. Results

3.1 Phosphorus release

Fig. 3 shows the DRP concentrations and the mass of DRP at both application rates (Table 5) in the overlying water over the study duration. All treatments, with the exception of the study control, released 90 % of the cumulative DRP within the first 5 to 10 h. The treatments which had the lowest DRP release, at the maximum legal application rate for a P index 1 soil, were (in ascending order of DRP release): AD biosolids, which had maximum concentrations of DRP of 0.36 mg L^{-1} and mass of P release of 22.1 mg m^{-2}; LS biosolids (0.46 mg L^{-1} and 28.0 mg m^{-2}); high ash MBM (0.69 mg L^{-1} and 43.1 mg m^{-2}); low ash MBM (1.14 mg L^{-1} and 70.5 mg m^{-2}); and TD biosolids (2.43 mg L^{-1} and 148.4 mg m^{-2}). The same pattern was obtained from the treatments applied at twice the maximum legal rate. At both application rates, the TD biosolids released more than double the mass/concentration released by the highest of the other treatments. There was no significant difference between the AD and LS biosolids applied at either rate ($p=0.516$ and $p=0.421$, respectively), but there was a significant difference between both types of MBM and the AD and LS biosolids applied at both the maximum legal and double the maximum legal application rates ($p<0.05$).

3.2 Metals

The concentrations of Cu, Fe and Mn are presented in Fig. 4-6. With the exception of TD and LS biosolids, all concentrations of metals were below the legal limits for the abstraction of drinking water (75/440/EEC; EEC 1975) when the biosolids and MBM were applied at the maximum legal rate. The concentrations of Cr, Ni and Zn, also tested in this study, were below the discharge limits (results not shown). Thermally dried biosolids exceeded the limits for Mn (Fig. 6) when applied at the maximum legal limit; this, combined with its high mass release of DRP (Fig. 3), indicates that it may not be safely used for land application. However, the tests in this study are indicative only, and plot/field scale testing would need to be conducted to confirm this finding. Anaerobically digested biosolids, low ash and high ash-content MBM remained within the limits at both application rates.

3.3 pH and DO measurements

The addition of biosolids and MBM increased the pH of the supernatant water at all times (1, 8 and 30 h) during the test (results not shown). Lime stabilised biosolids produced the largest increase in pH, producing values of approximately 10 for both application rates versus the study control (7.5).

The addition of MBM and biosolids to the grass reduced the DO of the supernatant water. Thermally dried biosolids removed the most DO from overlying water (75 – 80 % versus the control) after 8 h at the maximum legal and twice the maximum legal application rate (results not shown). This was followed by the LS biosolids, which removed between 65 – 70 % at both application rates; low ash MBM at 60 – 65 %; high ash MBM at 50 – 55 % and AD biosolids at 20 – 50 %.

4. Discussion

Maximum legal application rates of biosolids and MBM to P index 1 soil tested at laboratory-scale, showed that, with the exception of TD and LS biosolids, adherence to guidelines governing application rates based on nutrient and metal content can ensure minimal losses of nutrients and metals to surface runoff. However, to ensure correct application rates, regular soil, biosolids and MBM testing is crucial to minimise incidental losses (where an application is followed by a rainfall event). This experiment was conducted on soil with a low P content. Soil metal content, degree of P saturation, and other parameters, may affect the buffering capacity of the soil. Therefore, the results obtained in the present study are specific to one soil type. The application rates in the present study which had the lowest release of DRP (3.3 and 0.8 t DS ha^{-1}, respectively, for AD biosolids and high ash content MBM) were low compared to other studies, and had the AD and high ash content MBM been applied on the basis of their N content, the application rates would have been 14.7 and 2.5 t DS ha^{-1}, respectively, which could potentially give rise to surface runoff of P. For example, Joshua et al. (1998) found that over a 3-y period following a one-time application of AD biosolids, applied at rates of 0, 30, 60 and 120 t DS ha^{-1}, that both control (no application) and biosolids-amended plots were high in Fe, Al and Mn, which indicated that biosolids had no significant impact on potential metal release.

Although the focus of the present study was to determine the potential pollution threat following landspreading of MBM and biosolids, end-users are also interested in their ability to fertilise soil. There is a good body of literature which has examined their fertilisation potential. Siddique and Robinson (2004) mixed AD biosolids, poultry litter, cattle slurry and an inorganic P fertiliser with 5 soil types at rates equivalent to 100 mg P kg^{-1} soil and, following incubation at 25^{o}C for 100 d, found that biosolids and poultry litter had a slower rate of P release compared with cattle slurry and inorganic P fertiliser. This may indicate that they may have good long-term fertilisation potential. In a field-scale study, Jeng et al. (2006) applied MBM at application rates of 500, 1000 and 2000 kg MBM ha^{-1} to spring wheat and barley, along with a base fertilizer of 30 kg N ha^{-1} applied to a study control. The yield of spring wheat increased linearly with increasing application rates of MBM in comparison to the control. Further applications beyond 500 kg MBM ha^{-1} did not result in additional yields when the MBM was applied to barley. Jeng et al. (2006) also noted that supplementary mineral P resulted in no increase in the yield when 500 kg MBM ha^{-1} was applied. Chen et al. (2011) found that there was no difference in grain yields over a 4-y period between plots of spring barley and oats when treated with MBM and a mineral fertilizer applied at rates of 43, 64 and 86 kg P ha^{-1}.

The metal analysis in the present study shows that when spread at the maximum legal limit, only TD biosolids exceed the legal discharge limits for Mn (Fig. 6). However, like the other results quoted in this study, these results are indicative only and need to be verified at field-scale. A limitation of the runoff test is that it is the same mass of water that is present on the soil for the duration of the test and, consequently, it does not mimic overland flow. Therefore, the results achieved in the runoff test may be at variance to those from field-scale runoff experiments. Stehouwer et al. (2006) applied AD biosolids to land at a rate of 134 t DS ha^{-1} (much higher than the rates applied in the present study; Table 5) and determined from groundwater samples, that acidity generated from the application of the biosolids aided the mobilisation of Zn, Ni, Cu and Pb to a depth in excess of 1 m.

Release of pathogens into the environment is another concern associated with the land application of biosolids (Gerba and Smith, 2005). Zerzghi et al. (2010a) conducted a study on plots that were treated with 20 annual land applications of 8 and 24 t DS ha^{-1} of AD Class B liquid biosolids (containing 8 % DS) in order to establish the potential for soil microbial activity. Surface soil samples (0-30 cm), analysed 10 mo after the final application, showed no bacterial or viral pathogens present. In the same study, Zerzghi et al. (2010b) found that the microbial activity increased with increasing application rate of biosolids on the plots, but the bacterial diversity of the soil was not impacted negatively following the applications.

One of the major stumbling blocks in the use of biosolids and MBM as a low-cost fertiliser is the issue of public perception (Apedaile 2001). In Ireland, companies that produce products for the food and drinks industry will not allow the use of the raw materials produced from agricultural land which has been treated with biosolids (FSAI 2008; Board Bia 2009). This limits their use as a fertiliser at the current time.

5. Conclusions

The results of this study show that AD biosolids, and high ash and low ash-content MBM may be applied to land within maximum legal application limits without any adverse risk of runoff of P or metals. Thermally dried biosolids released high amounts of DRP and Mn into the supernatant water in a runoff test. Lime stabilised biosolids released low amounts of DRP into the supernatant water, but exceeded the legal limit for Mn (when applied at the maximum legal application rate, based on a P index 1 soil) and Fe (when applied at twice the maximum legal application rate). The runoff test is a simple, quick test for the determination of the potential risk of nutrient and metal loss following application of biosolids or MBM to an intact grassland core. The results, while indicative only, allow comparison to be made between amendments when applied at the same rate. The findings of this study need to be verified at laboratory-scale (using a rainfall simulator), plot and field-scale. In addition, further research is required to determine their effect on the physical and chemical properties of soil.

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Captions for Figures

Fig. 1 Percentage of sludge produced landspread for a range of European countries. Data for Germany, Greece, Poland, Spain, Sweden and the United Kingdom obtained from the Eurostat website (European Commission, 2011a; European Commission, 2011b). Data for Ireland taken from reports on the urban waste water discharges in Ireland published by the EPA (EPA, 2003; EPA, 2004; EPA, 2007 and EPA, 2009).

Fig. 2 Flow chart for the determination of the maximum application rate of biosolids or meat and bone meal to be applied to land.

Fig. 3 Release of DRP into overlying water for both the control and the treatments over the 30-h test period.

Fig. 4 Copper concentrations present in overlying water at the end of 30 h after the start of the runoff test. The concentrations measured for applications at the agronomic rate and twice the agronomic rate are denoted by ‘1’ and ‘2’, respectively. The dashed line represents allowable concentration limit as per Council Directive 75/440/EEC (EEC, 1975).

Fig. 5 Iron concentrations present in overlying water at the end of 30 h after the start of the runoff test. The concentrations measured for applications at the agronomic rate and twice the agronomic rate are denoted by ‘1’ and ‘2’, respectively. The dashed line represents allowable concentration limit as per Council Directive 75/440/EEC (EEC, 1975).

Fig. 6 Manganese concentrations present in overlying water at the end of 30 h after the start of the runoff test. The concentrations measured for applications at the agronomic rate and twice the agronomic rate are denoted by ‘1’ and ‘2’, respectively. The dashed line represents allowable concentration limit as per Council Directive 75/440/EEC (EEC, 1975).

Table 1. Limit values for metal concentrations in sludge and soil.

Limit values	Copper (Cu)	Nickel (Ni)	Lead (Pb)	Zinc (Zn)	Cadmium (Cd)	Chromium (Cr)	Mercury (Hg)
	--- mg kg^{-1} ---						
European Union[a]							
For concentrations of heavy metals in soil	50 - 140	30 - 75	50 - 300	150 – 300	1 - 3	-	1 - 1.5
For heavy metal concentrations in sludge for use in agriculture	1,000 - 1,750	300 -400	750 - 1,200	2,500 - 4,000	20 - 40	-	16 - 25
	--- kg $ha^{-1}y^{-1}$ ---						
For amount of heavy metal that may be applied annually to soil	12.0	3.0	15.0	30.0	0.15	-	0.1
Ireland							
For average annual rate of addition of metal (over a 10 yr period)[b]	7.5	3.0	4.0	7.5	0.05	3.5	0.1

[a] Limit values taken from Directive 86/278/EEC (EEC, 1986)

[b] Limit values taken from (Fehily Timoney and Company, 1999)

Table 2. Explanation of different Category 1, 2 and 3 meat and bone meal (Enterprise Ireland, 2011)

Category	Waste includes
1	Very high risk material, including BSE-infected (or suspected of being infected) carcasses, animal parts that have been given prohibited substances, and floor waste where specific risk material is created.
2	Medium risk material, including animals that have died on a farm, digestive tract content, and the animal by-products that exceed allowable levels of specific substances (e.g. therapeutic drugs).
3	Lower risk material, including material which is fit for human consumption (catering waste, raw meat and fish, hides and skins); pieces of slaughtered animals that are fit for human consumption but, for commercial reasons, are not permitted for human consumption; or, due to manufacturing or packaging defects, animal by-products derived from the processing of materials intended for human consumption; and blood from non-diseased ruminants.

Table 3. Metals and nutrient content for treatments used in this study. Standard deviations, where tested, are in brackets.

Waste type	Nutrients					Metals						
	OM	**Tot-P**	**WEP**	**Tot-N**	**Dry Matter**	**Cu**	**Ni**	**Pb**	**Zn**	**Cd**	**Cr**	**Hg**
	%	------- mg kg^{-1} dry solids -------			**%**	----------------------------------- mg kg^{-1} dry solids -----------------------------------						
Anaerobically digested	52.1(0.83)	6916	73.8(9.5)	6.8	21.6(0.7)	169.4	30.0	27.3	576.1	0.7	30.0	<0.5
Thermally dried	81.2(0.04)	7600	413.4(54.4)	30.8	86.1(0.0)	356.7	22.2	66.2	640.3	0.7	25.2	1.3
Lime stabilised	43.9(3.62)	6332	301.6(53.0)	3.1	27.1(1.3)	361.8	20.6	23.0	428.2	0.8	25.4	0.5
Meat and Bone Meal (High ash)	73.8(0.95)	27.9	1749.0(38.3)	39.7	92.1(0.2)	6.4	0.5	1.9	67.9	<0.3	1.1	<0.3
Meat and Bone Meal (Low ash)	53.7(0.64)	31.1	1021.2(25.0)	59.1	91.8(0.5)	10.6	1.5	1.9	86.2	<0.3	3.1	<0.3

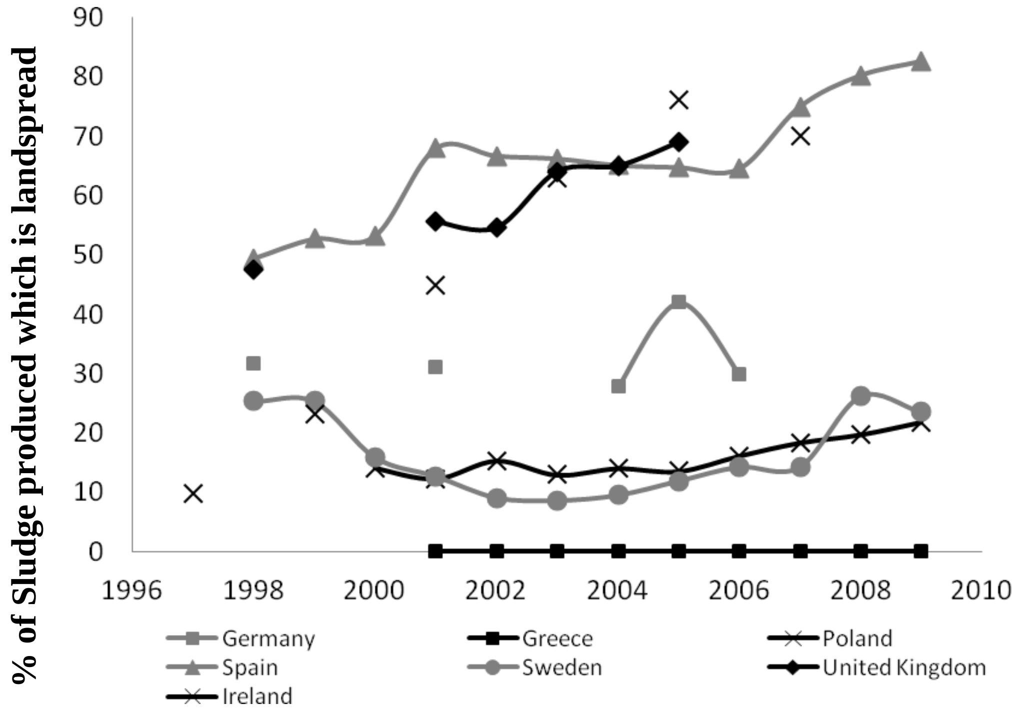
Table 4. Classification of soil used in this study. Standard deviations are in brackets.

WEP (g kg^{-1})	0.013 (0.001)
Morgan's P (mg L^{-1})	1.5 (0.5)
Lime requirement	6.1 (0.4)
Potassium (mg L^{-1})	87.6 (2.0)
Magnesium (mg L^{-1})	258.1 (3.1)
Organic matter (%)	18.3 (0.6)

Table 5. Application rates of biosolids and meat and bone meal (MBM) to the soil in this study using a P index 1 soil.

Waste type	Maximum legal application rate		Double the maximum legal application rate	
	Wet weight	Dry solids	Wet weight	Dry solids
	tonnes ha^{-1}			
AD biosolids	14.8	3.3	29.6	6.6
TD biosolids	3.3	3.0	6.5	6.0
LS biosolids	18.0	5.2	35.9	10.4
High ash MBM	0.9	0.8	1.7	1.6
Low ash MBM	0.8	0.7	1.5	1.4

Fig 1



% of Sludge produced which is landspread
90
80
70
60
50
40
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
2010
Germany
Greece
Poland
Spain
Sweden
United Kingdom
Ireland

Fig 2

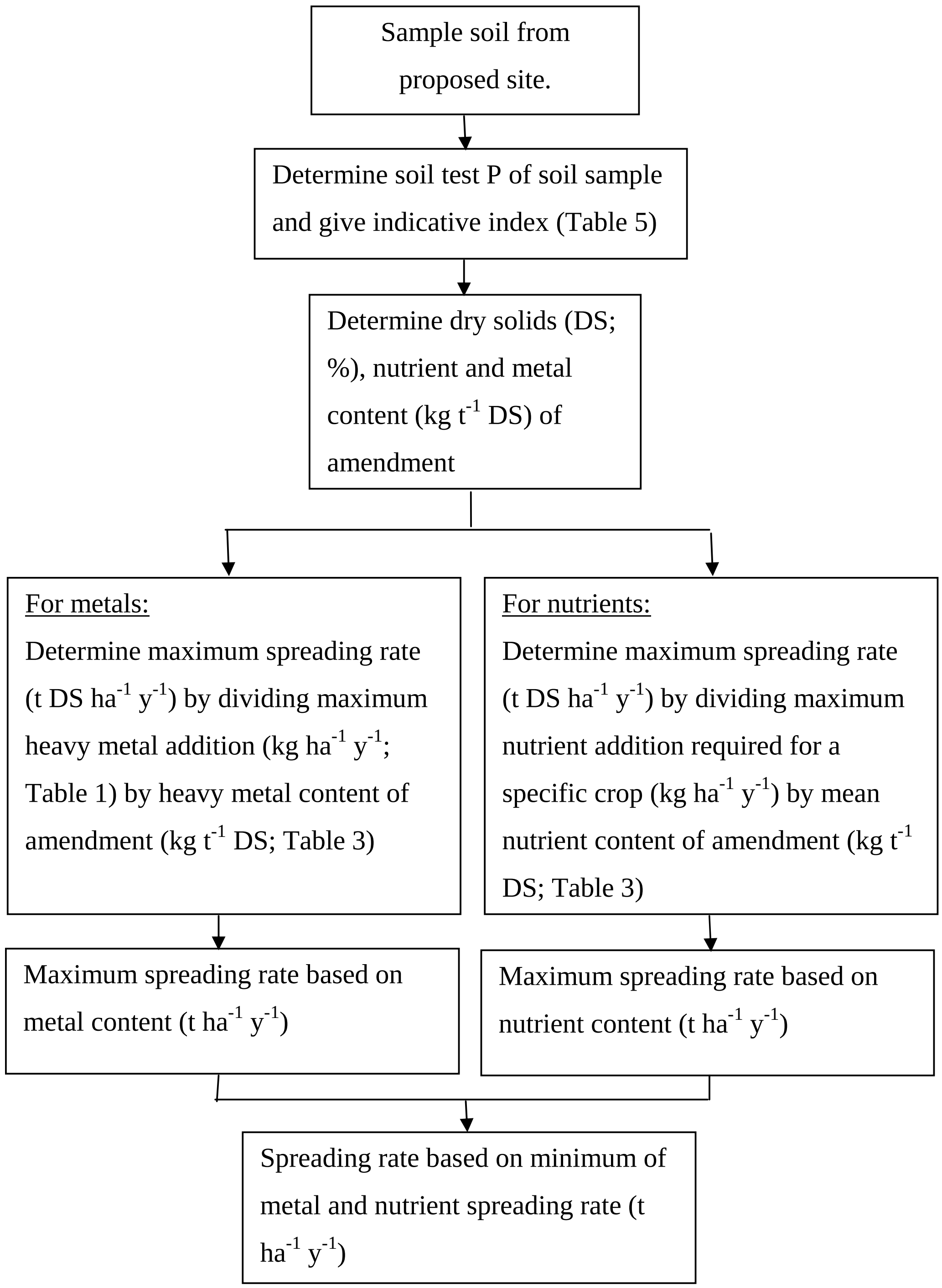
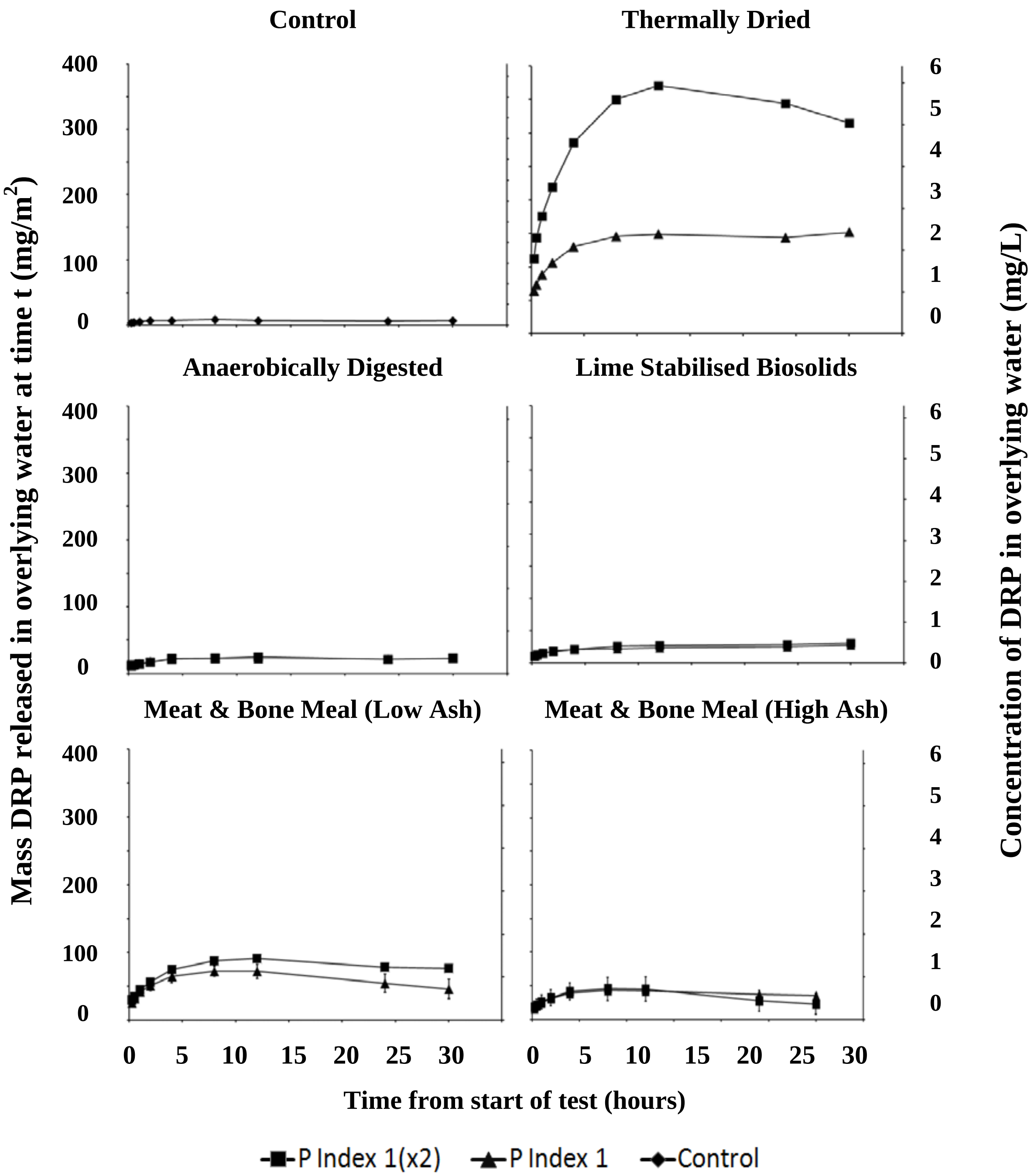

Sample soil from proposed site.
Determine soil test P of soil sample and give indicative index (Table 5)
Determine dry solids (DS; %), nutrient and metal content (kg t^{-1} DS) of amendment
For metals:
Determine maximum spreading rate (t DS ha^{-1} y^{-1}) by dividing maximum heavy metal addition (kg ha^{-1} y^{-1}; Table 1) by heavy metal content of amendment (kg t^{-1} DS; Table 3)
For nutrients:
Determine maximum spreading rate (t DS ha^{-1} y^{-1}) by dividing maximum nutrient addition required for a specific crop (kg ha^{-1} y^{-1}) by mean nutrient content of amendment (kg t^{-1} DS; Table 3)
Maximum spreading rate based on metal content (t ha^{-1} y^{-1})
Maximum spreading rate based on nutrient content (t ha^{-1} y^{-1})
Spreading rate based on minimum of metal and nutrient spreading rate (t ha^{-1} y^{-1})

Fig 3



Control
Thermally Dried
Anaerobically Digested
Lime Stabilised Biosolids
Meat & Bone Meal (Low Ash)
Meat & Bone Meal (High Ash)
400
300
200
100
0
6
5
4
3
2
1
0
0 5 10 15 20 25 30
Mass DRP released in overlying water at time t (mg/m²)
Concentration of DRP in overlying water (mg/L)
Time from start of test (hours)
P Index 1(x2)
P Index 1
Control

Fig 4

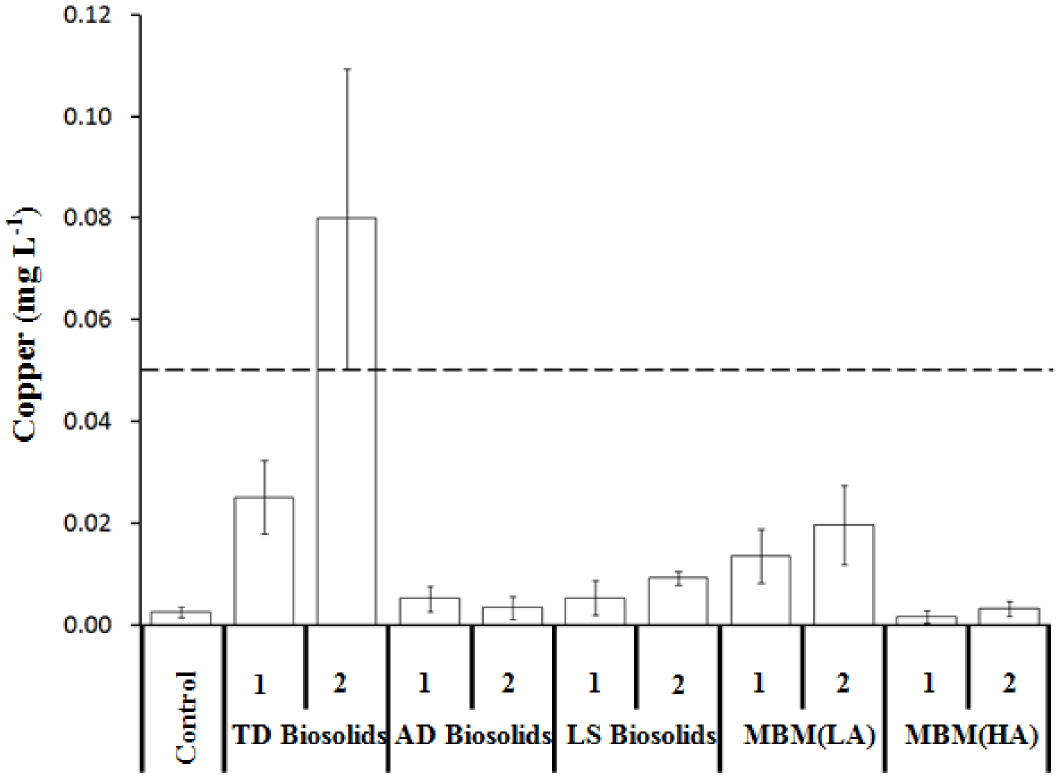

Copper (mg L-1)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Control
1
2
TD Biosolids
1
2
AD Biosolids
1
2
LS Biosolids
1
2
MBM(LA)
1
2
MBM(HA)

Fig 5

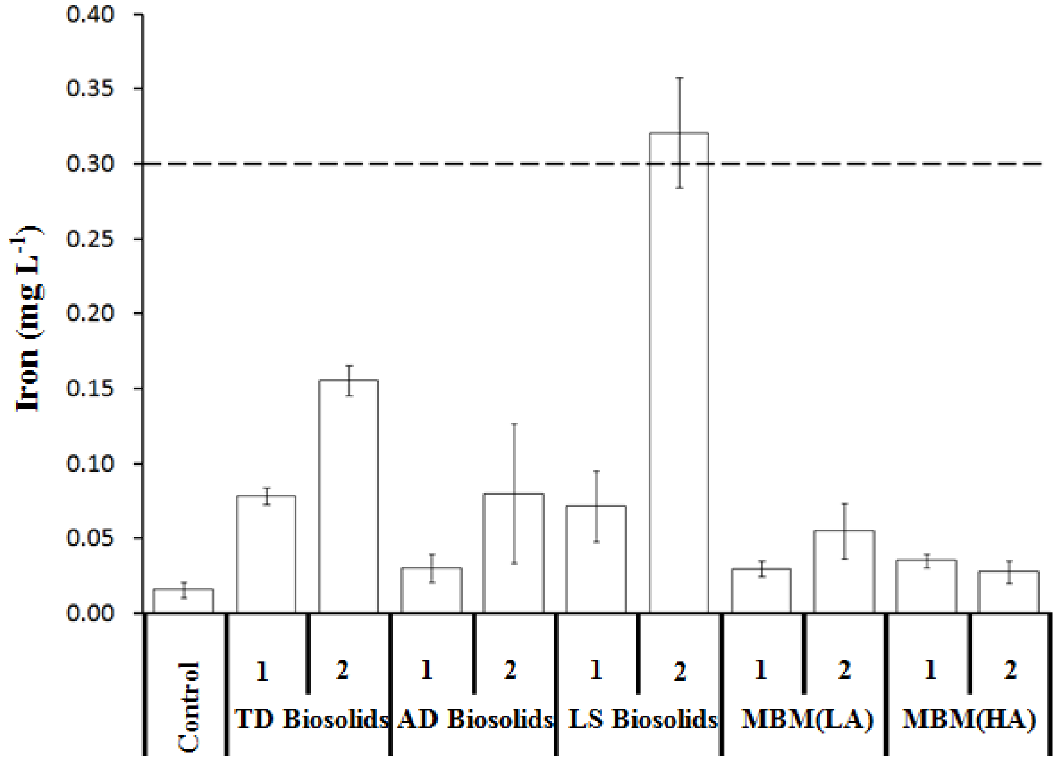
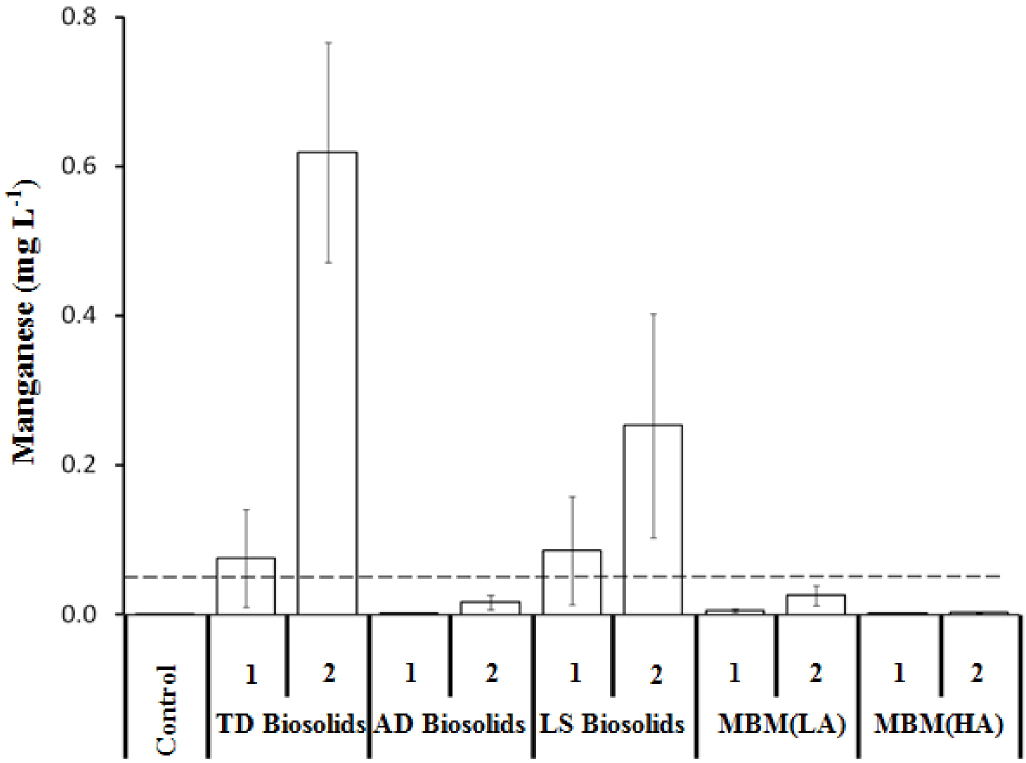

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Iron (mg L-1)
Control
1
2
TD Biosolids
1
2
AD Biosolids
1
2
LS Biosolids
1
2
MBM(LA)
1
2
MBM(HA)

Fig 6


Manganese (mg L^{-1})
0.8
0.6
0.4
0.2
0.0
Control
1
2
1
2
1
2
1
2
1
2
TD Biosolids
AD Biosolids
LS Biosolids
MBM(LA)
MBM(HA)