Fertilization effects of organic waste resources and bottom wood ash: results from a pot experiment

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A pot experiment was conducted to study the fertilization effects of four N- and P-rich organic waste resources alone and in combination with K-rich bottom wood ash at two application rates (150 kg N ha^{-1} + 120 kg K ha^{-1}, 300 kg N ha^{-1} + 240 kg K ha^{-1}). Plant-available N was the growth-limiting factor. 48–73% of N applied with meat and bone meal (MBM) and composted fish sludge (CFS) was taken up in aboveground biomass, resulting in mineral fertilizer equivalents (MFE%) of 53–81% for N uptake and 61–104% for yield. MFE% of MBM and CFS decreased for increasing application rates. Two industrial composts had weak N fertilization effects and are to be considered as soil conditioners rather than fertilizers. Possible P and K fertilization effects of waste resources were masked by the soil's ability to supply plant-available P and K, but effects on plant-available P and K contents in soil suggest that the waste resources may have positive effects under more nutrient-deficient conditions.

Key words: meat and bone meal, fish sludge, compost, nitrogen use efficiency, mineral fertilizer equivalent

Introduction

Today's agriculture relies on the application of mineral fertilizers to return plant nutrients to agricultural land. However, global resources of fossil fuel and phosphate rock, raw material for the production of mineral fertilizers, are limited. According to current calculations, economically exploitable P will be exhausted within 50–100 (Cordell et al. 2009) to 300–400 years (van Kauwenbergh 2010), and several investigations suggest that we might already have passed peak oil. In order to ensure food security in the future, we will have to reduce our dependence on mineral fertilizers and to replace linear nutrient flows by nutrient cycles.

Returning waste to agricultural land by the application of waste-based fertilizer products is a systemic approach to meeting the challenging task of future food supply. There are many derivatives from the food industry as well as waste products from industry and bioenergy plants that are considered as waste despite considerable contents of valuable plant nutrients. The potential of these by-products as fertilizers in agriculture is still largely unexploited.

Meat and bone meal (MBM) is a by-product from industrial slaughtering operations with considerable amounts of N (~8%), P (~5%) and Ca (~10%) (Jeng et al. 2006), making it interesting as fertilizer to agricultural crops. Each year, Norwegian slaughterhouses produce 30000 Mg of low-risk category 3 MBM, containing about 2400 Mg N and 1500 Mg P (Haraldsen et al. 2011b). Assuming N and P fertilization effects of respectively 80% and 50% (Jeng et al. 2004, 2006), Norwegian MBM has the potential to compensate for 1900 Mg N and 750 Mg P, commensurating 2% and 10% of N and P that was applied to Norwegian agricultural land with artificial fertilizers in 2010 (SSB 2011).

Previous studies have shown that MBM is a predictable organic N fertilizer with similar fertilization effects as mineral fertilizers (Salomonsson et al. 1994, 1995, Jeng et al. 2004, 2006, Chen et al. 2011), and that it has a positive effects on the baking performance of wheat (*Triticum aestivum* L.), as well as on common quality parameters in barley (*Hordeum vulgare*) and oat (*Avena sativa*) (Fredriksson et al. 1997, 1998, Chen et al. 2011). Phosphorus in MBM is partly present as organic P in the meat fraction, which can easily be taken up by the plants, but the the largest amount is present as apatite in the bone fraction, requiring H^+ to become available to plants and making the P fertilization effect of MBM dependent on soil pH (Jeng et al. 2006, Ylivainio et al. 2008). Due to low N:P ratios (< 2–3, Jeng et al. 2004, 2006, Ylivainio et al. 2008, Jeng and Vagstad 2009), it has previously been recommended that MBM fertilizer rates should be adjusted to the plants' P demands and to the long term P fertilization effect of the material, rather than to N contents (Jeng et al. 2006).

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Fish sludge is the accumulation of N- and P-rich faeces and feed residues on the ground of hatcheries and fish farms, which is today commonly discharged directly into the sea (Norwegian Ministry of Fisheries and Coastal 2008). Based on the number of Norwegian hatcheries for salmon and trout and their production volume we estimated that there were collected around 40000–50000 Mg of fish sludge in 2010. With a dry matter (DM) content of 10% and respectively 4 – 5% N and 2 – 3% P, Norwegian fish sludge contains 200–250 Mg N and 80–150 Mg P. According to previous studies on fertilization effects both untreated and anaerobically treated fish sludge have the potential to result in larger biomass production and N and P uptake in crops than conventional animal manure (Gebauer and Eikebrokk 2006, Uhlig and Haugland 2007). Fish sludge from freshwater hatcheries is better suited as fertilizer than fish sludge originating from seawater fish farms, which can result in sodium (Na) uptake by the crops (Teuber et al. 2005). Treating fish sludge in a composting reactor developed by the company Global Enviro AS produces material that is in its consistency and composition very similar to MBM, and studies of Haraldsen and Krogstad (2011) let assume that fertilization effects of MBM and composted fish sludge (CFS) are comparable.

Biomass ashes, residues from thermal combustion activities, are potential Ca, P, K and Mg fertilizers, provided that their heavy metal contents are low (Mozaffari et al. 2002, Haraldsen et al. 2011b, Schiemenz et al. 2011). Still, biomass ashes have so far mainly been considered as liming products (Knapp and Insam 2011). Narrow Ca:K ratios (< 3 or less) and high K contents (> 6 g $(100g)^{-1}$ DM) are the requirements to ashes when used as alternative fertilizer products in order to keep their neutralizing effect in accordance with annual acidification of agricultural soils (Haraldsen et al. 2012). There are large variations in terms of quality of biomass ashes produced by Norwegian bioenergy plants and so far there is a lack of knowledge about available material of a quality fulfilling the governmental, regulative (Norwegian Ministry of Agriculture 2003) and agronomic requirements.

There are several challenges, which prevent farmers from applying by-products from food-industry and other industrial waste products to agricultural land. Some of the major drawbacks associated with the re-use of waste in agriculture are minimum requirements according to material quality (Norwegian Ministry of Agriculture 2003, §10), energy- and cost-intensive transport of products with low dry matter contents, as well as the challenge of even application of bulky or dusty waste. Moreover, actual fertilization and liming effects of waste products are largely unknown, and NPK ratios in waste material are usually unbalanced in comparison to the plants' needs (Haraldsen and Krogstad 2011, Haraldsen et al. 2011b). Combining various waste resources potentially overcomes the challenge of unbalanced NPK ratios in waste material.

Several studies have already tested the concept of recycled NPK fertilizer based on waste resources and results have been promising. Haraldsen et al. (2011b) found in a pot experiment, where combined waste resources were applied to spring cereals, that fertilization with MBM and bottom wood ash (BWA) can result in significantly larger yields than fertilization with MBM alone, and in yields as large as after fertilization with mineral compound fertilizer (Haraldsen et al. 2011b). Haraldsen and Krogstad (2011) combined various N-rich waste resources with BWA in a two-year pot experiment with spring cereals as experimental crops and suggested that BWA has potential P and K fertilization effects if N is in sufficient supply. Pradhan et al. (2010) studied the fertilization effect of human urine combined with wood ash during a field experiment on red beet (*Beta vulgaris*) and concluded that the waste-based fertilizer combination can increase plant biomass production compared to mineral compound fertilizer. Kuba et al. (2008) found that addition of wood ashes to organic waste can improve compost quality and nutrient balances in the end-product. Still, more research has to be done on the fertilization effects of specific waste resources and their combinations to improve the utilisation of containing nutrients, and to re-close nutrient cycles.

The intention of the present study was to contribute to the development of waste-based compound fertilizer products by investigating (i) N use efficiency and (ii) P and K fertilization effects of various waste resources. Since N turned out to be the growth-limiting factor, in the present paper we focus on N fertilization effects of N-rich organic waste resources included in the experiment. Fertilization effects were determined by aboveground biomass production and nutrient uptake of Italian ryegrass (*Lolium multiflorum* var. *italicum*) in response to fertilizer application and compared with the effects of mineral compound fertilizer.

Materials and methods

Waste resources

Waste resources included in the experiment all originated from industrialized food production or other industry activities and are briefly described in Table 1.

Table 1. Description of waste resources.

Waste resource	Abbreviation	Nutrients	Description
Bottom wood ash	BWA	K	Biomass ash originating from a grate fired boiler system of the company Akershus Energi AS, which is located in Årnes (63°96'N, 10°23'E), Norway. Parent material was timber unfeasible for industrial use and residues from the local mill. Both sources were clean of or had a low contents of heavy metals.
Meat and bone meal	MBM	N and P	Stabilized, sanitized and pelletized meat and bone meal originating from the slaughterhouse in Mosvik (63°82'N, 11°01'E), Norway.
Composted fish sludge	CFS	N and P	Parent material was a mixture of feed residues and excrements from salmon hatchery of the company Åsen settefisk AS (63°61'N, 11°05'E) in Trøndelag, Norway. After dewatering of the sludge using mechanical filters, the material was composted for 18 h in a reactor developed by the company Global Enviro AS.
Neutral Dynea compost	Dynea 2009	N	Industrial compost. Parent material was based on an effluent containing polymers of urea, melamine and formaldehyde from the international company Dynea ASA, which is located in Lillestrøm (59°96'N, 11°05'E), Norway. The effluent was cleaned through a microbial filter. The N-rich sediment including microbial biomass of the filter was mixed with wood chips before the material was composted in windrows outdoors.
Acid Dynea compost	Dynea 2004	N	Industrial compost with the same parent material as Dynea 2009. During storage polymers of formaldehyde break down to formic acid and lower the pH to around 3.5.

Samples of each of the waste resources were analysed before application. pH was determined according to NS 4720 (1979) or NS-EN 13037 (2000). The total contents of P and K as well as of trace elements (Cd, Cr, Cu, Hg, Ni, Pb, Zn) were determined after dissolution with nitric acid (7 M HNO_3) according to NS 4770 (1994) by simultaneous ICP-AES according to NS EN ISO 11885 (2009). Total N contents were determined by the modified Kjeldahl method (EN 13654-1 2001). NO_2- and NO_3-N and NH_4-N were determined after extraction with 2 M KCl (Henriksen and Selmer-Olsen 1970, Selmer-Olsen 1971) by a Konelab Aqua 60 analyser. To analyse the content of total organic carbon (TOC), the material was first washed with a 2 M HCl solution to remove any inorganic carbon. Then a crushed sample was burned at 925 °C using a Perkin Elmer 2400 CHN analyser. Readily available P-AL, K-AL, Mg-AL and Ca-AL were determined on ICP-AES after extraction with a solution composed of 0.4 M acetic acid and 0.1 M ammonium lactate (pH 3.75) in a solid-to-solution ratio of 1:20 (w/v) (Egnér et al. 1960). Table 2 summarizes the chemical properties of the waste resources that were applied as fertilizer in the experiment.

MBM and CFS had high contents of N and P. N:P ratios were 2 and 4, respectively. BWA was due to its high K content and solubility of the nutrient in ashes considered as potential K fertilizer. BWA also contained some P but plant-availability was assumed to be low according to P-AL analysis. Dynea compost is an N-rich industrial by-product of the industry business Dynea ASA in Lillestrøm, Norway. Even if the annual production is minor, Dynea compost is a valuable local resource and studies on the material were, therefore, included in the experiment.

Table 2. Chemical characteristics of waste resources. See Table 1 for explanation of the abbreviations of the waste resources.

Parameter, unit	BWA	MBM	CFS	Dynea 2009	Dynea 2004
pH	12.0	6.5	5.7	7.3	3.5
DM, g $(100g)^{-1}$	100	98	86	29	43
Loss on ignition, g $(100g)^{-1}$ DM	0.23	71	88	66	63
Total N, g $(100g)^{-1}$ DM	0.1	9.0	6.9	7.3	7.8
C:N ratio	1	5	7	5	5
NH_4-N, g $(100g)^{-1}$ DM	0.00046	0.03100	0.25850	0.00887	0.06410
NO_2- and NO_3-N, g $(100g)^{-1}$ DM	0.00036	0.00028	0.00019	0.08400	0.17960
N_{min} (% of total N)	0.81	0.35	3.75	1.27	3.12
Total P, g $(100g)^{-1}$ DM	1.7	4.5	1.7	0.2	0.3
P-AL, g $(100g)^{-1}$ DM	0.19	2.00	1.60	0.09	0.06
N:P ratio	0.06	2	4	37	31
N:P-AL ratio	1	5	4	84	130
Total K, g $(100g)^{-1}$ DM	7.7	n.d.	0.15	n.d.	n.d.
K-AL, g $(100g)^{-1}$ DM	6.4	0.3	0.3	0.1	0.0
Mg-AL, g $(100g)^{-1}$ DM	1.5	0.1	0.3	0.1	0.0
Ca-AL, g $(100g)^{-1}$ DM	8.6	4.2	2.8	0.8	0.0

DM = dry matter, N_{min}= ammonium-N and nitrate-N, AL = extraction with 0.4 M acetic acid and 0.1 M ammonium lactate, n.d. = not determined.

All of the waste resources fulfilled the Norwegian requirements for waste-based fertilizer products. For content of heavy metals in the waste resources see Table 3. MBM was in quality class 0 according the Norwegian regulations considering the content of heavy metals in the material. Therefore, there are no restrictions regarding the amount of MBM that could be applied to agricultural land other than the plants' demands, and that it should not be applied on areas for grazing and production of grass for feeding of production animals unless it is blended with a mixing component, according to the EU by-product ordinance 1774/2002. BWA and CFS were in quality class I, their use on agricultural land would therefore be restricted to 40 Mg DM ha^{-1} and 10 yr^{-1}. Both Dynea 2009 and Dynea 2004 were in quality class II. Therefore, their use on agricultural land would be restricted to 20 Mg DM ha^{-1} and 10 yr^{-1} (Norwegian Ministry of Agriculture 2003, §10 and §27). According to the current legislation on organic farming in Norway (Mattilsynet 2009), the use of MBM and untreated BWA is also allowed on organic agricultural fields. The parent material of CFS is in its consistency and composition similar to animal manure and can, therefore, be defined as animal manure of fish. The content of heavy metals in CFS was at the same level as Norwegian animal manure from various types of animals (Paulsrud et al. 1997).

Table 3. Contents of heavy metals (mg kg^{-1} dry matter) in waste resources. See Table 1 for explanation of the abbreviations of the waste resources.

Parameter	BWA	MBM	CFS	Dynea 2009	Dynea 2004
Cd	0.60	0.02	0.40	0.21	0.27
Cr	15.00	1.60	1.70	15.00	16.00
Cu	75.00	8.70	11.00	42.00	59.00
Hg	0.00	0.01	0.01	0.18	0.73
Ni	16.00	1.80	0.53	32.00	22.00
Pb	7.80	1.10	0.35	33.00	31.00
Zn	200.00	99.00	290.00	150.00	84.00

Soil

The experimental soil was a sandy loam with large fractions of gravel and organic matter with origin in Kise (60°78'N, 10°81'E) in the municipality Ringsaker in Norway, where rocks are calciferous dolomites and sediments are morainic soils (NGU 2011). Table 4 is an overview over the distribution of the size of soil particles, which was determined according to Elonen (1971).

Table 4. Size of soil particles in the experimental soil.

Unit	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	Clay
mm	2–0.6	0.6–0.2	0.2–0.06	0.06–0.02	0.02–0.006	0.006–0.002	<0.002
%	21.4	25.1	11.0	9.4	9.4	6.6	17.1

Table 5 describes the chemical characteristics of the soil used in the experiment, which was taken from an experimental field with organic production in 2009. Analyses were conducted in 2009. TOC, P-AL, K-AL, Mg-AL and Ca-AL were determined by the methods as described for the waste resources. K-HNO_3, an estimate for exchangeable and non-exchangeable K reserves in the soil, was determined after boiling the soil in a 1 HNO_3 solution (Pratt 1965). pH was determined in a soil water suspension of 1:2.5 (v/v). Contents of readily available P-AL were low, contents of readily available K-AL were intermediate and K reserves measured as acid-soluble K-HNO_3 were low (Bioforsk 2003). Low nutrient contents in the soil were supposed to enable the evaluation of NPK fertilization effects of the waste resources. Due to the soil's origin in calciferous dolomite rocks, it contained considerable amounts of Mg-AL and large amounts of Ca-AL (Landbrukets analysesenter s.a.). The waste resources were not assessed regarding their contents of Mg and Ca, and adequate amounts in the soil were, therefore, desirable to prevent deficiency of Mg and Ca in the plants.

Table 5. Chemical characteristics of the experimental soil at the beginning of the experiment (measured in 2009).

pH	TOC	Total N	C:N	P-AL	K-AL	K-HNO_3	Mg-AL	Ca-AL
	g $(100g)^{-1}$	g $(100g)^{-1}$		mg $(100g)^{-1}$	mg $(100g)^{-1}$	mg $(100g)^{-1}$	mg $(100g)^{-1}$	mg $(100g)^{-1}$
6.4–6.5	3.1–3.3	0.27– 0.31	11.3–11.8	2.5–3.0	8.2–8.7	34–38	15–17	284– 304

TOC = total organic carbon, AL = extraction with ammonium lactate, HNO_3= extraction with nitric acid.

In 2009, 2/3 of the soil was used for a pot experiment with Chinese cabbage (*Brassica rapa*), where different liming strategies were tested, and in 2010 spring wheat (*Triticum aestivum*) was grown to test the fertilization effect of digestate from biogas plants. In both cases, fertilization was adapted to the plants' needs and a decrease or increase of nutrient contents in the soil was, therefore, not expected. About 1/3 of the soil had been stored under outdoor conditions for the last three years, when we mixed all of the soil thoroughly during set-up of the experiment. Possible influences of previous activities were, therefore, evenly distributed on all experimental treatments. The soil was sieved at a mesh width of 4 mm to sort out the gravel before filling of experimental pots. After the experiment had finished, soil samples from all of treatments were taken (0–20 cm). pH, Ca-AL, K-AL, Mg-AL, Na-AL, P-AL, NO_2- and NO_3-N and NH_4-N were determined as described.

Experimental design

The experiment was conducted outdoors under a transparent, synthetic roof in Ås, Norway (59°39'N, 10°45'E). Kick/Brauckmann pots (7.5 l with a top diameter of 21.5 cm) were randomized side by side on a table where the plants were protected from precipitation but otherwise exposed to daylight and outdoor climate. Due to wind protection on the north and east side of the roof, average temperature was somewhat higher than data for the growing season, which is presented in Table 6.

Table 6. Average temperature (°C) for each month compared to the standard reference period (Lippestad 2011).

	Temperature (°C)	
	2011	Reference period [a]
May	10.5	10.3
June	15.0	14.8
July	17.0	16.1
August	15.3	14.9
September	12.3	10.6

[a] Monthly temperature average in the period 1961–1990.

The plants were irrigated three times a week. Each pot was watered up and kept at a water level of 0.25–0.35 m^3 m^{-3}, which was estimated to represent a water potential between –10 and –100 kPa in the experimental soil. To measure the soil water content a HH2 moisture meter with a Delta-T Devices soil moisture sensor SM 200 was used.

The experimental crop was Italian ryegrass (*Lolium multiflorum* var. *italicum* cv. 'Macho'), which commonly clearly responds to fertilization (Frame 1992) being a good indicator of the amount of plant-available nutrients in soils. Hence, it was used to study mineralization rates and fertilization effects of the waste resources by uptake of nutrients in aboveground biomass. In the field, seed rates of 30–40 kg ha^{-1} are recommended when Italian ryegrass is sown in pure stand (Lund et al. 2011). In the pot experiment a seed rate of 30 kg ha^{-1} was chosen. This amount is equivalent to 0.11 g pot^{-1}.

The experiment was designed to supply plants with N, P and K similar to that supplied with the compound fertilizer Yara Fullgjødsel® 18 – 3 – 15 (minNPK). All of the four N-rich waste resources were tested alone and in combination with K-rich BWA. Fertilizer combinations were compared with the effect of minNPK. An unfertilized treatment and only calcium nitrate (minN) were included to study the soil's ability to supply plant nutrients. Additionally, there were reference treatments with minN in combination with BWA and BWA alone. Each treatment was tested at two application rates, calculated with respect to the amount of total N (Kjeldahl-N) and total K content (extraction with 7 M HNO_3) in N-rich waste and K-rich BWA, respectively. Application rates (150 kg N ha^{-1} + 120 kg K ha^{-1} by 300 kg N ha^{-1} + 240 kg K ha^{-1}) were chosen based on fertilizer recommendations for pastures with three cuts in Norway (Bioforsk 2003), and calculated based on the surface area of the pots. The soil depth was with 20 cm in accordance with the depth of cultivated topsoil. There were three replicates for each treatment. The experimental design is presented in Table 7.

Planting took place on 9 May 2011. The upper 5 cm of soil in the pots were removed and fertilizer was applied evenly on the soil together with the seeds. Then the upper soil layer was placed back on top. Hence, seeds were placed deeper than intended, and deeper than commonly recommended for grasses, resulting in delayed germination and reduced biomass production during the first harvest (Table 8). During the first weeks, weeds were removed to avoid interplant competition until the experimental crop was fully established. The pots did not receive any further fertilization throughout the summer.

Biomass was harvested manually with scissors at a height of 1.5 cm from soil surface on 21 June, 19 July, 17 August and 27 September 2011. For each pot, plant material was dried at 40 °C for one week, and dry matter production was calculated. Chemical analyses were conducted for one pooled sample per treatment. Total N in plant material was determined by the Dumas method (NS-EN 13654-2 2001). Total tissue concentrations of P, K, Mg, Ca and micronutrients were determined as described for the waste resources. Nutrient uptake (kg ha^{-1}) was computed by multiplying concentration of the pooled samples by the yield of each replication.

Table 7. Amount of waste resources applied with contents of mineral N (N_{min}), total P, P-AL and total K/K-AL as kg ha^{-1}. See Table 1 for explanation of the abbreviations of the waste resources.

	Application rates									
	150 kg N ha^{-1} + 120 kg K ha^{-1}					300 kg N ha^{-1} + 240 kg K ha^{-1}				
Treatment	Amount	N_{min}	total P	P-AL	K/-AL[a]	Amount	N_{min}	total P	P-AL	K/-AL[a]
BWA	1558	0	26	3	120	3117	0	53	6	240
minNPK	852	150	22	22	124	1705	300	44	44	249
minN	968	150	0	0	0	1935	300	0	0	0
minN + BWA	2526	150	26	3	120	5052	300	53	6	240
MBM	1701	0.5	75	33	5	3401	1	150	67	10
MBM + BWA	3259	0.5	101	36	125	6518	1	203	73	250
CFS	2528	5.6	37	35	7	5056	11	74	70	13
CFS + BWA	4086	5.6	63	38	127	8172	11	127	75	253
Dynea 2009	7110	0.5	4	0	2	14220	1	8	0	4
Dynea 2009 + BWA	8668	0.5	31	3	122	17337	1	61	6	244
Dynea 2004	4495	4.7	6	1	0	8991	9	12	2	0
Dynea 2004 + BWA	6054	4.7	32	4	120	12107	9	65	8	240

[a] K in BWA was calculated based on total K. K in other material is based on K-AL. AL = extraction with 0.4 M acetic acid and 0.1 M ammonium lactate.

Data analysis

Nitrogen use efficiency (NUE%, Salomonsson et al. 1994, 1995, Jeng et al. 2004) was calculated as follows:

$$\text{NUE}\ (\%) = \frac{100 \times [N_{up} - N_{up}(c)]}{N_{applied}} \quad (1)$$

where
NUE = N use efficiency
N_{up} = N in aboveground biomass as sum of all four harvests (kg N ha^{-1})
c = unfertilized control treatment
$N_{applied}$ = Total N amount applied with fertilizer treatment

Mineral fertilizer equivalent (MFE%, Delin 2011), which is defined as the application rate of mineral fertilizer N (kg N ha^{-1}) to which the fertilization effect of organic waste on yield or N uptake (Y) is equivalent, expressed as percentage of total N applied, was calculated as follows:

$$\text{MFE\%} = 100 \times X_1 / X_{tot} \quad (2)$$

where
MFE = mineral fertilizer equivalent
X_{tot} = 150 or 300 kg N ha^{-1}

$$X_1 = (Y_1 - b) / a \quad (3)$$

Y_1 = yield or N uptake obtained with waste resource
a and b are slope and intercept obtained from linear regression by the minimum least squares method of yield or N uptake (Y) obtained with mineral fertilizer (minNPK) on mineral N application rate (X = 0, 150 and 300 kg N ha^{-1}, respectively).

Multiple comparisons between treatments were statistically performed by one-way analysis of variance (ANOVA) including all treatments. Tukey's studentized range test was applied with a significance level of $p \le 0.05$. The program package SAS/STAT (SAS Institute Inc. 1989) was used for the statistical analysis.

Results

Effects of fertilizer treatments on biomass production

The highest fertilizer rates of minNPK and minN treatments resulted in the largest total yields (Table 8). The regression of yield (Y) on mineral N application rate (X) gave the following response function: Y = 24.46X + 2157.95 (R^2=0.98).

Table 8. Mean (n=3) biomass production (kg ha^{-1}) as influenced by the fertilizer treatments. See Table 1 for explanation of the abbreviations of the waste resources.

Treatment	Amount applied	1st harvest	2nd harvest	3rd harvest	4th harvest	Total
Control	0	489	877	445	146	1958
BWA	150	593	1068	552	326	2539
	300	451	1387	628	329	2795
minNPK	150	669	3355	1722	482	6228
	300	716	4796	2911	872	9295
minN	150	401	2556	2407	673	6038
	300	268	2370	4403	1839	8879
minN + BWA	150	490	3095	2271	431	6287
	300	231	2073	3960	1994	8258
MBM	150	549	2882	1353	621	5405
	300	354	3062	2570	837	6823
MBM + BWA	150	558	3178	1510	720	5966
	300	544	3552	1886	665	6647
CFS	150	717	2795	1146	680	5338
	300	713	3396	1801	930	6840
CFS + BWA	150	713	2794	1104	656	5266
	300	553	3621	2059	991	7224
Dynea 2009	150	409	1285	617	391	2701
	300	492	1116	578	388	2574
Dynea 2009 + BWA	150	490	876	421	315	2103
	300	381	1250	647	450	2728
Dynea 2004	150	452	1789	733	445	3418
	300	428	2096	1023	479	4026
Dynea 2004 + BWA	150	441	1931	813	454	3638
	300	320	2034	960	442	3755
MSD [a], $p \leq 0.05$		455	1242	1076	555	1965

[a] MSD = minimum significant difference.

Application of MBM and CFS resulted in similar biomass production. All in all, total yields were smaller after MBM and CFS fertilization than after mineral fertilizer treatments of the same N amount, but differences were only significant for the higher rates (300 kg N ha^{-1}). According to calculations of MFE% for yield (Table 9) MBM and CFS could respectively achieve 89–104% and 85–97% of the total yield of 150 kg N ha^{-1} minNPK and 61–64% and 64–69% after fertilization with the total yield of 300 kg N ha^{-1} minNPK. Among Dynea compost treatments, only the effect of 300 kg N ha^{-1} Dynea 2004 was significantly different from the unfertilized control treatment. Dynea 2009 and 2004 compensated for up to 15% and for 34–40% of the total yield after fertilization with 150 kg N ha^{-1} minNPK and for 6–8% and 22–25% of the total yield after fertilization with 300 kg N ha^{-1} minNPK (Table 9). Dynea 2004 resulted generally in larger yields than Dynea 2009, but differences between effects of the two compost types were not significant. Application of BWA alone resulted in equally small yield as the unfertilized control reference and there was no significant effect of BWA in combination with minN or N-rich waste resources on biomass production in comparison to the same treatment without BWA.

At the first harvest, yields were very small (Table 8). However, despite poor establishment there was no need of reseeding, as reduced germination was compensated by tillering. Especially minN treatments resulted in poor establishment and 300 kg N ha^{-1} minN + BWA gave the smallest yield. 150 kg N ha^{-1} CFS without BWA and 300 kg N ha^{-1} minNPK resulted in the largest yields, but their effects were only significantly different from the poorly established minN + BWA (300 kg N ha^{-1}) treatment. During the second harvest, 300 kg N ha^{-1} minNPK treatments resulted in significantly larger biomass than all other treatments except for 300 kg N ha^{-1} CFS + BWA. MinN treatments of the lowest application rate (150 kg N ha^{-1}) resulted in biomass production at the same level as all MBM and CFS treatments, and 300 kg N ha^{-1} minN treatments tended to result in smaller yields than lower application rates (150 kg N ha^{-1}). At times of the third harvest, plants that had been fertilized with minN, were well developed and 300 kg N ha^{-1} minN treatments resulted in the largest yields among all treatments. There were no significant differences between effects of minNPK, MBM and CFS treatments of the same application rate. At the fourth harvest, yields were again small in general. Biomass production after fertilization with 300 kg N ha^{-1} minN was significantly different from all other treatments (Table 8).

Effects of fertilizer treatments on N in plant biomass and soil

N uptake of unfertilized plants indicated that about 39 kg N ha^{-1} was directly plant-available from the experimental soil. Plants utilized 86–107% of N applied with minNPK and minN (NUE%, Fig. 1). After MBM and CFS fertilization, respectively, plants utilized 49–73% and 48–50% of N applied. After MBM and CFS fertilization, plants took up less N than after mineral fertilizer treatments of the same N amount, but differences were only significant for 300 kg N ha^{-1} treatments. None of the Dynea compost treatments was significantly different from the unfertilized control treatment regarding N uptake in biomass. Plants took up 3–11% of N applied with Dynea 2009 and 16–28% of N applied with Dynea 2004 (NUE%, Fig. 1).

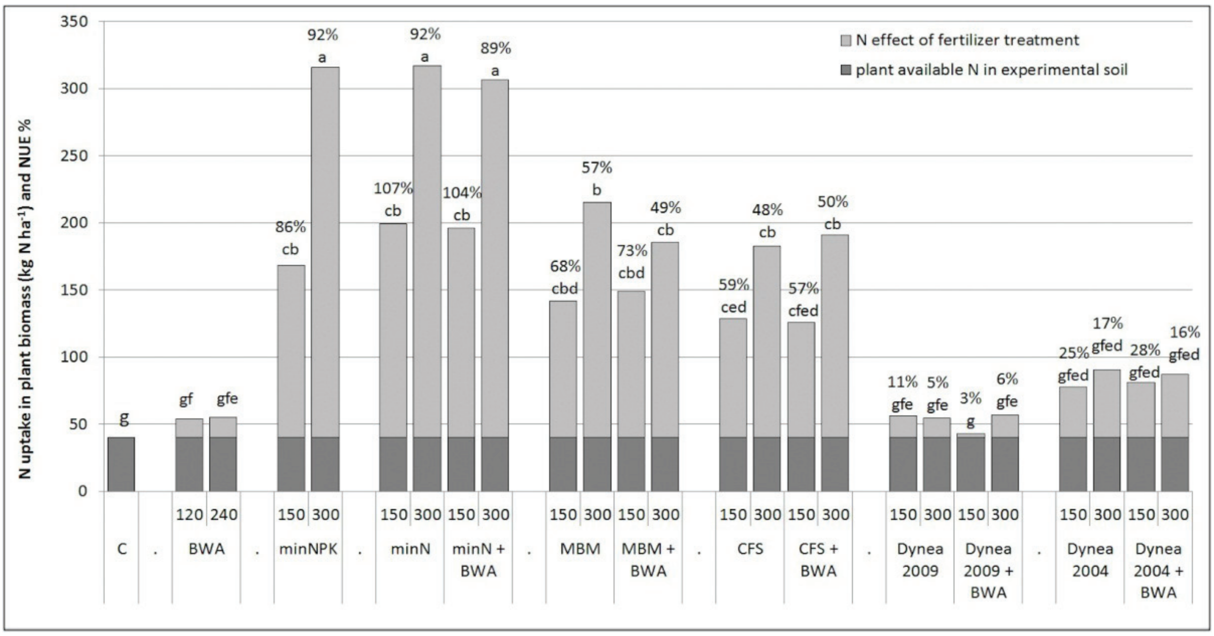

Fig. 1. Total N uptake in plant biomass (kg N ha^{-1}) as influenced by fertilizer treatments (150 kg N ha^{-1} + 120 kg K ha^{-1}, 300 kg N ha^{-1} + 240 kg K ha^{-1}). Percentages refer to NUE (%). Means followed by the same letter are not statistically different. See Table 1 for explanation of the abbreviations of the waste resources, C = unfertilized control treatment.

The regression of N uptake (Y) on mineral N application rate (X) gave the following response function: Y = 0.92X + 36.21 (R^2=0.98). MFE% for N uptake showed that MBM and CFS, could, respectively, compensate for 76–81% and 65–67% of N uptake after fertilization with 150 kg N ha^{-1} minNPK, and for 54–65% and 53–56% after fertilization with 300 kg N ha^{-1} minNPK. Dynea composts could compensate for 5–32% of N uptake after fertilization with 150 kg N ha^{-1} minNPK, and for 7–19% after fertilization with 300 kg N ha^{-1} minNPK (MFE% for N uptake, Table 9).

43 days after MBM and CFS fertilization (first harvest), 5–13% of the N harvested during the entire experimentalp-eriod was present in aboveground biomass, and 71 days after MBM and CFS fertilization (second harvest) 50–67% of the N harvested during the entire experimental period was present in aboveground biomass. 100 days after MBM and CFS fertilization (third harvest) 86–89% of totally harvested N was taken up in aboveground biomass.

Analyses of soil samples that were taken at the last day of the experiment suggested that practically all plant-available N was taken up by the plants. There were no significant differences between the treatments regarding residual mineral N in the soil. The minimum significant difference was 0.2 mg $(100g)^{-1}$ soil for NH_4-N and NO_2- and NO_3-N measurements, respectively. Assuming soil density of 1.2 g cm^{-3} and soil depth of 20 cm, there was around 10 kg ha^{-1} of mineral N left in the soil on the day of the last harvest (results not shown).

Table 9. Mineral fertilizer equivalents (MFE%) of organic waste resources for yield and N uptake.
See Table 1 for explanation of the abbreviations of the waste resources.

	Application rates			
	150 kg N ha^{-1} + 120 kg K ha^{-1}		300 kg N ha^{-1} + 240 kg K ha^{-1}	
Treatment	Yield	N uptake	Yield	N uptake
MBM	89	76	64	65
MBM + BWA	104	81	61	54
CFS	87	67	64	53
CFS + BWA	85	65	69	56
Dynea 2009	15	14	6	7
Dynea 2009 + BWA	–2	5	8	7
Dynea 2004	34	30	25	19
Dynea 2004 + BWA	40	32	22	18

Effects of fertilizer treatments on P and K in plant biomass and soil

There were no significant differences in P uptake as kg P ha^{-1} after fertilization with minNPK or MBM and CFS at any rate. Overall, utilization of fertilized P tended to be best after CFS application, which resulted in the highest P uptake for all rates and combinations but there were no significant differences to minNPK and MBM fertilization (Table 10). MinN fertilization resulted in fairly low P concentration in plant biomass, especially during the first two harvests (results are not shown). However, there were no significant differences between total P uptake as kg P ha–1 after fertilization with minN and minNPK.

All MBM treatments and 300 kg N ha^{-1} CFS and CFS + BWA resulted in significant effects on P-AL values in the soil in comparison to the unfertilized control treatment. All MBM treatments except for 150 kg N ha^{-1} MBM increased P-AL in the soil from low to high values according to Norwegian classifications (Krogstad et al. 2008). Also BWA tended to increase P-AL values in the soil, but significant effects on P-AL values in the soil were only found for 150 kg N ha^{-1} MBM and 300 kg N ha^{-1} CFS, when treatments with and without BWA were compared (Table 10).

All plants were sufficiently supplied with K and there were no significant effects of BWA on K uptake as kg K ha^{-1} compared to the same treatments without BWA. The amount of plant-available K in the soil measured as K-AL decreased after all treatments in the course of the experiment. BWA application tended to result in larger amounts of plant-available K (K-AL) in the soil compared to the same treatments without BWA, and BWA treatments of both rates (120 and 240 kg K ha^{-1}) were significantly different from the unfertilized control regarding K-AL contents in the soil (Table 10).

Table 10. Uptake of total P and K in plant biomass (kg ha^{-1}) and effects of fertilizer treatments on contents of P-AL and K-AL [mg (100g)$^{-1}$soil] and pH. See Table 1 for explanation of the abbreviations of the waste resources.

	Application rates									
	150 kg N ha^{-1} + 120 kg K ha^{-1}					300 kg N ha^{-1} + 240 kg K ha^{-1}				
	P	K	P-AL	K-AL	pH	P	K	P-AL	K-AL	pH
Treatment	kg ha^{-1}	kg ha^{-1}	mg (100g)$^{-1}$ soil	mg (100g)$^{-1}$ soil		kg ha^{-1}	kg ha^{-1}	mg (100g)$^{-1}$ soil	mg (100g)$^{-1}$ soil	
Control	7	79	3	3	6.7	7	79	3	3	
BWA	9	106	5	7	6.8	9	114	5	8	6.8
minNPK	16	258	3	4	6.5	23	412	4	4	6.3
minN	14	254	3	4	6.8	18	317	3	4	6.6
minN + BWA	15	290	4	5	7.0	19	350	4	6	6.9
MBM	15	230	7	4	6.7	19	265	11	4	6.4
MBM + BWA	17	259	12	6	6.8	18	282	13	6	6.8
CFS	18	227	4	4	6.6	24	255	6	3	6.4
CFS + BWA	19	240	6	5	6.8	24	315	10	9	6.7
Dynea 2009	9	110	3	3	6.7	9	112	3	3	6.5
Dynea 2009 + BWA	8	90	4	6	6.8	9	114	4	7	6.6
Dynea 2004	11	146	3	3	6.6	12	160	3	4	6.4
Dynea 2004 + BWA	11	155	4	6	6.8	11	166	5	7	6.7
MSD [a], $p \le 0.05$	6	85	3	3	0.5	6	85	3	3	0.5

[a] MSD = minimum significant difference.

Effects of fertilizer treatments on soil pH

Overall, there were only minor effects of fertilizer treatments on soil pH as result of buffering reactions in the experimental soil, which were due to relatively high concentrations of organic material and relatively high clay content (Table 4, Table 5). BWA fertilization tended to result in higher pH values than the unfertilized control and all fertilizer combinations with BWA showed a tendency of higher soil pH than equivalent fertilizer treatments without BWA but effects were not significant.

Discussion

Nitrogen use efficiency and mineral fertilizer equivalents of organic waste resources

N uptake in aboveground biomass (NUE%) after MBM (49–73%) and CFS (48–59%) fertilization and N mineralization over time were similar to results of previous studies on mineralization dynamics of MBM. Delin and Engström (2010) concluded after incubation studies with various organic waste resources under Swedish field conditions that 65% of N applied with MBM can be released within 30–50 days and that N mineralization is flattening out thereafter. Also reduced biomass production at times of the fourth harvest during the present experiment (Table 8) can be explained by decreasing N mineralization of MBM and CFS with time, as indicated by negligible contents of residual mineral N in the soil at the last day of the experiment. Mondini et al. (2008) studied mineralization dynamics of MBM under laboratory conditions for 14 days and found that 50% of N applied with MBM was mineralized within the course of the experiment. Consequently, scarce biomass production at the first harvest of the present experiment (Table 8) was surprising, also because ryegrass is commonly characterized by early plant development (Fustec et al. 2005). However, it was probably too deep placement of seeds that resulted in delayed germination and initial growth, rather than of a lack of mineralized N. Total net-mineralization of N applied with MBM and CFS was higher than NUE% let assume, as N uptake in root biomass was not taken into account for the calculation of NUE%.

Relative N replacement values of MBM and CFS (MFE% for N uptake, Table 9) are well in accordance with studies of Delin et al. (2011), who investigated fertilization effects of MBM during two pot experiments with Italian ryegrass, and somewhat lower than equivalent values calculated based on previous studies that compared N uptake in grain after fertilization with MBM or CFS with mineral N fertilization (76% in Salomonsson et al. 1995, 91% in Jeng et al. 2004, 71–124% in Chen et al. 2011, 80–90% in Haraldsen et al. 2011a). Lower MFE% for N uptake of MBM and CFS in the present study can be explained by the experimental design, which intentionally avoided denitrification and N leaching losses. Irrigation was adapted to the specific soil characteristics so that denitrification losses were reduced and closed plant–soil systems set up by Kick/Brauckman pots prevented nitrate from leaching to deeper soil layers. All of the studies with cereals as experimental crops referred to were conducted under field conditions or as pot experiments with an intended leaching episode. According to studies by Haraldsen et al. (2011a) and Haraldsen and Krogstad (2011) N-rich waste is less prone to nitrate leaching than mineral N fertilizer. Consequently, we may assume that immediately soluble mineral fertilizers would have come out less favourable in comparison to organic waste resources, if leaching had occurred.

MFE% for yield tended to be higher than MFE% for N uptake, indicating that MBM and CFS have the potential to result in almost equally large yield as mineral fertilizers, but in lower N concentration. If MBM or CFS is applied as fertilizer to cereals, lower N concentration might result in lower grain quality. This assumption is, however, not in accordance with previous studies by Salmonsson (1994, 1995), Fredriksson et al. (1997, 1998) and Chen et al. (2011) who found equally good quality parameters of cereals after fertilization with MBM as after the mineral reference treatment during field experiments.

It has to be taken into account that high MFE% values can only be achieved, if N release matches with the crops' demands in time. In cereal production the time for N recovery is much shorter than the duration of the present experiment, where ryegrass was used as a method to study nutrient supply over time. If MBM or CFS is used as fertilizer to cereals, N will have to be mineralized before ear emergence, as cereal plants mainly utilize nutrients from their own vegetative reserves after this physiological stage (Spiertz and de Vos 1983). In Norway, grain is harvested 100–120 days after sowing, at a time when only 86–89% of total N taken up in plants after MBM and CFS fertilization was taken up by ryegrass during present experiment. MFE% of MBM and CFS might therefore be clearly lower than presented in the present study, if applied as alternative N fertilizer to cereals.

Relationship between fertilizer amount and N fertilization effect

The effects of the highest application rates of MBM and CFS (300 kg N ha^{-1}) on plant biomass were significantly different from effects of mineral fertilizer treatments of the same rate, which was puzzling because of equally good effects of the lowest rates (150 kg N ha^{-1}) (Table 8). Decreasing effectiveness of organic fertilizers for increasing amounts is known from application of manure to agricultural land (Bioforsk 2003), and has moreover earlier been described by Boen and Haraldsen (2011) after application of increasing amounts of composted biowaste to perennial ryegrass (*Lolium perenne*) as well as by Trøite (2007) after studies on different organic fertilizers in a pot experiment with barley and by Kristoffersen et al. (2012) after application of increasing amounts of liquid residues from biogas production to barley. Likewise, Delin and Engström (2010) found reduced mineralization after incubation of larger amounts of various organic waste types.

A possible explanation for reduced fertilization effects of 300 kg N ha^{-1} MBM and CFS in comparison to 150 kg N ha^{-1} is a lack of oxygen when microbial activity increased with increasing amounts of organic material. Application of organic material can considerably reduce oxygen availability in the soil atmosphere with associated negative effects on plant and root growth as shown by Hossain et al. (2005) who studied the composition of soil gases after application of increasing amounts of manure. Delin and Engström (2010) suggested that reduced net-N mineralization of larger amounts of organic material could be explained by denitrification of mineralized N as result of anaerobic conditions due to increased microbial oxygen consumption.

Another possible explanation for decreasing fertilizer efficiency for organic waste resources at higher rates are phytotoxic effects of fatty acids, which might have accumulated when organic material was degraded under oxygen depleted conditions. Fatty acids are known to have harmful effects on germination and seedling root and shoot development (Schuman and McCalla 1976), and an accumulation after fertilization with 300 kg N ha^{-1} MBM and CFS might therefore have resulted in decreased nutrient uptake.

Oxygen deficiency and phytotoxic effects of fatty acids as result of MBM and CFS treatments might have had a particularly strong effect on biomass production during the present experiment as fertilizers were not evenly distributed in the soil, but concentrated at a depth of 5 cm in the same layer as the seeds. In similar studies on effects of organic fertilizers, the material had been mixed into the top layer to simulate even distribution by harrowing (Haraldsen et al. 2011a) or into the entire soil volume similar to incorporation by ploughing (Boen and Haraldsen 2011). However, neither oxygen supply nor the development of fatty acids was measured in the present experiment and their effects remain therefore assumptions.

N fertilization effects of Dynea composts

Dynea composts showed reduced N fertilization effects for all rates and combinations resulting in small biomass production throughout the season (Fig. 1, Table 8). This indicates that organic N in Dynea composts was rather recalcitrant. Slow N mineralization is typical for mature compost material (Amlinger et al. 2003, Bar-Tal et al. 2004, Boen and Haraldsen 2011) irrespective of its C:N ratio, as carbon in compost is of low availability and hence not well suited as source of energy to soil microorganisms. Asdal and Breland (2003) even suggested that mature compost material releases mineral N so slowly that the amount of inorganic N probably is almost equivalent to plant-available N during a growing season. N in Dynea composts was mainly present as polymers of urea, melamine and formaldehyde. Although Dynea composts originated from industrial processes, net-N mineralization of these composts seemed to be at the same level as net-mineralization of mature composts based on biological organic waste materials. Based on analyses of chemical properties prior to the experiment 0.5–1 kg mineral N ha^{-1} and 4.7–9 kg mineral N ha^{-1} were applied with Dynea 2009 and Dynea 2004, respectively (Table 7). Obviously these amounts were far from sufficient to supply plants with N. Better fertilization effects of the older material can possibly be explained by larger initial amounts of mineral N in Dynea 2004 compared with Dynea 2009. The results suggest that Dynea composts can generally be applied in relatively large amounts without intensive effects on plant growth. Therefore, they are rather to be classified as soil conditioners with potentially positive effects on physical, chemical or biological soil characteristics than as fertilizers, which are defined as products with the key task of supplying plants with nutrients (Norwegian Ministry of Agriculture 2003, appendix 1).

P fertilization effects of waste resources

Even though initial contents of plant-available P in the soil were estimated to be low (P-AL, Table 5, Krogstad et al. 2008), the soil still supplied plants with sufficient P. Therefore, P fertilization effects of waste residues did not become visible in biomass production or as P uptake during the present experiment. Sufficient P uptake despite low soil P contents can be explained by grasses being fairly tolerant to low P availability in soils in comparison to other crops (Caradus 1980) and by Italian ryegrass being adapted to P deficient conditions due to fast root development (Kemp and Blair 1994). Even plants fertilized with minN with initially low P concentration in plant tissue, achieved total yields at the same level as plants fertilized with minNPK. Delayed biomass production initiated by initial P deficiency after minN fertilization could be compensated due to the closed plant-soil system set up by Kick-Brauckmann pots, which prevented nitrate-N from leaching. Under field conditions nitrate-N would probably already have been lost by the time when plants were sufficiently supplied with P.

CFS tended to result in higher P uptake than MBM, even though larger total P amounts were applied with MBM (Table 7, Table 10). This is in agreement with studies of Haraldsen and Krogstad (2011) who found significantly higher P uptake by wheat after fertilization with CFS of codfish hatcheries than after MBM amendments of the same origin as in the present study. It seems, therefore, as if CFS-P is better available to plants than MBM-P, and that P fertilization effects of CFS are independent of pH, whereas MBM-P apparently is more soluble in acidic than in neutral or alkaline soils (Jeng et al. 2006, Ylivainio et al. 2008).

Surprisingly, MBM fertilization resulted in an amount of soluble P in the plant-soil system (P-AL in the soil and P taken up by plants) that was higher than total P applied with the material (Table 7, Table 10). Similar effects of MBM on plant-available P measured as P-AL were observed by Haraldsen et al. (2011a), when MBM was applied to barley. According to findings of present and previous studies, one has to question if P-AL analysis is suited as indicator for P fertilization effects of MBM. The present investigation indicated a need for more thorough studies on the actual P fertilization effect of MBM, and evaluations of the P-AL method as indicator for P availability in different types of organic wastes applied as P fertilizer.

K fertilization effect of bottom wood ash

K fertilization effects of BWA were hidden by the soil's ability to supply plant-available K. This is in accordance with studies of Øgaard et al. (2002), who found no yield response of plants on K fertilizers when soil K exceeded 8 mg K-AL $(100g)^{-1}$. The amount of plant-available K in the experimental soil measured as K-AL was between 8.2 and 8.7 mg K-AL $(100g)^{-1}$ and, therefore, high enough to result in luxury K uptake in ryegrass even after application of minN, which supplied plants with sufficient N but no K. Even though K fertilization effects of BWA were not evident as biomass production or uptake in plant biomass, K-AL values in the soil indicated potential fertilization effects (Table 10). Also Ferreiro et al. (2011) observed an increase of K contents in the soils of mountain pastures after fertilization with wood ashes. Therefore it is likely that BWA has a long-term K fertilization effect when K contents in the soil are depleted. As BWA from Akershus Energi AS did not significantly increase soil pH (Table 10), it seems to be well suited for annual application to agricultural land and hence as ingredient in waste-based NPK fertilizer products.

To detect P and K fertilization effects of respective MBM, CFS and BWA, long-term experiments should be conducted, which guarantee sufficient supply of N and all other essential nutrients except the one to be studied.

Conclusion

Mineral N was the growth-limiting factor in the current experiment and fertilization effects of organic waste resources were therefore determined by their net-mineralization rate. 48–73% of N applied with meat and bone meal and composted fish sludge was taken up in aboveground biomass, resulting in mineral fertilizer equivalents of 53–81% for N uptake and 61–104% for yield. Decreasing mineral fertilizer equivalents for increasing fertilizer rates were most likely caused mainly by unintended concentrated application of organic waste resources. Meat and bone meal and composted fish sludge represent valuable alternative N fertilizers and potential ingredients in waste-based NPK fertilizer products, provided that they are included in crop rotations with N-fixing legumes or that their N-fertilization value is enriched with mineral N. Dynea composts were characterized by weak N fertilization effects, as is typical for mature compost material, and are thus to be classified as soil conditioners rather than fertilizers. Possible P and K fertilization effects of waste resources were masked by the soil's ability to provide plant-available P and K, but effects of waste resources on plant-available P and K contents in soil suggest that plant growth responses may be expected under more P- and K-deficient conditions.

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