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Efficiency of combined waste resources as N and P fertiliser to spring cereals

Results from a 2-year pot experiment

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Sammendrag:

N-rike avfallsmaterialer viste potensielt gode effekter som N gjødsel til korn. P gjødseleffekt til kjøttbeinmel avtar med økende pH i jorda, mens P i bunnaske ser ut til å ha høy plantetilgjengelighet. K gjødseleffekten til bunnaske ble skjult av jordas evne til å bidra med plantetilgjengelig K.

Summary:

N-rich waste resources have potentially good effects if applied as fertiliser to spring cereals. P fertilisation effects of meat and bone meal are strongly determined by soil pH, whereas P in bottom wood ash seems to have almost the same availability as easily soluble P in mineral fertilisers. K fertilisation effects were hidden by the soils ability to provide plants with plant available K.

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1. Summary

Many waste resources from different parts of the food chain contain considerable amounts of valuable plant nutrients. NPK ratios in waste resources are usually not in accordance with the plants' needs but could be improved by combination into alternative compound fertilisers. To study the fertilisation effect of combined waste resources, we conducted a 2-year pot experiment with a nutrient-deficient sand peat mixture as experimental soil and barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*) as first- and second year experimental crops.

Fertilisation effects of meat and bone meal (MBM), composted catering waste (CCW) and composted fish sludge (CFS), which all contain N and P but only negligible amounts of K, were studied alone and in combination with K-rich bottom wood ash (BWA). Waste resources were applied at two fertiliser levels (80 kg N ha^{-1} + 35 kg K ha^{-1}; 160 kg N ha^{-1} + 70 kg K ha^{-1}), which were based on the total N- and K-content in N-rich waste and BWA, respectively. Fertilisation effects of waste resources were compared with two merchandised organic compound fertilisers that are based on MBM and vinasse (Eko 8353 and Eko 6383), mineral compound fertiliser Yara Fullgjødsel® (minNPK), calcium nitrate (minN), minN with BWA, only BWA and an unfertilised control treatment.

During the first year of the experiment, when shower precipitation was simulated at Zadoks 13-14 and when drought forced cereals to ripen earlier than physiologically intended, organic waste resources showed relative N use efficiency of 60-120% in grain compared with mineral compound fertiliser and mineral fertiliser equivalents on grain yield were between 50-90%. Under controlled conditions during the second year of the experiment, organic waste resources showed relative N use efficiency of 30-60% in grain compared with mineral compound fertiliser, and mineral fertiliser equivalents on grain yield were between 30-80%.

The experiment indicated that plant availability of MBM-P is strongly determined by soil pH, whereas P in BWA can have almost the same availability as easily soluble P in mineral fertilisers. To be able to predict the P fertilisation effect of P-rich waste resources, further studies on the reliability of analytical methods and their synchronisation with crop responses are needed.

Potential K fertilisation effects of BWA were hidden by the soil's ability to provide plant-available K during the first year, but increased K uptake in aboveground biomass at sufficient N supply and increased amounts of plant-available K in the soil during the second year of the experiment indicate that the K fertilisation value of BWA might be detected by a long term experimental approach with controlled supply of N and P.

2. Introduction

Many waste resources from different parts of the food chain contain considerable amounts of valuable plant nutrients, making them interesting as alternative fertiliser products. NPK concentrations in waste material are, however, usually not in accordance with the plants' needs. Unbalanced nutrient ratios of waste resources can reduce their fertilisation effects and may result in accumulation of unexploited, valuable nutrients in the soil or in nutrient losses with associated environmental challenges. Fertilisation effects of waste resources could be improved by combining various waste streams into alternative compound fertilisers. Previous studies have already tested the concept of alternative NPK fertilisers based on waste combinations and have shown increased fertilisation effects after combination of waste in comparison to fertilisation effects of raw materials alone (Bougnom et al. 2012; Brod 2011; Haraldsen et al. 2011a; Pradhan et al. 2010).

The following waste resources were included in the present study:

Meat and bone meal (MBM), a by-product from industrial slaughtering operations, contains considerable amounts of N (8 %) and P (5 %) in addition to Ca (10 %) (Jeng et al. 2006), and is a known alternative fertiliser product. Previous studies have shown that MBM can be used as predictable organic N fertiliser with similar fertilisation effects as mineral fertilisers (Salomonsson et al. 1994; Salomonsson et al. 1995; Jeng et al. 2004; Chen et al. 2011), and according to Jeng et al. (2006) MBM can compensate for around 50% of P in mineral fertiliser during first year after application.

Also food waste contains considerable amounts of essential plant nutrients. Global Enviro International AS has developed a process that removes fat and water in advance to an aerobe treatment, and that seems to result in an end product with better fertilisation effects than regular compost material as indicated by Haraldsen et al. (2011b), who found that reactor-composted catering waste (CCW) can cause equally high N uptake in grain as mineral compound fertiliser when applied to barley (*Hordeum vulgare*).

Fish sludge is the accumulation of faeces and feed residues on the ground of hatcheries and fish farms. Despite considerable contents of N (4-5%) and P (2-3%, Blytt et al. 2011), Norwegian fish sludge is today commonly discharged directly into the sea (Norwegian Ministry of Fisheries and Coastal 2008), even though both untreated and anaerobically treated fish sludge has the potential to result in higher biomass production and N and P uptake in crops than conventional animal manure (Gebauer & Eikebrokk 2006; Uhlig & Haugland 2007). Treating fish sludge in a reactor developed by Global Enviro International AS produces material that is in its consistency and composition very similar to MBM. The fertilisation effect of composted fish sludge (CFS) has earlier been tested by Brod (2011) during a pot experiment with ryegrass (*Lolium perenne)* as experimental crop, who found that CFS of salmon hatcheries can have equally good fertilisation effects as MBM with reduced effects on residual P in the soil due to a wider N:P ratio.

Bottom wood ash (BWA) can contain considerable contents of K, additionally to Ca and Mg, as well as some P and trace elements. K in BWA is easily soluble and the material has therefore potential K fertilisation effects (Ohno & Erich 1990; Demeyer et al. 2001; Haraldsen et al. 2011a).

The objective of the present study was to contribute to the development of alternative NPK fertilisers based on waste resources by

(i) determining N use efficiency of waste resources and their mineral fertiliser equivalents
(ii) determining P and K fertilisation effects of various waste resources

Fertilisation effects were determined by straw and grain production and nutrient uptake of barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*) in response to fertiliser application.

3. Materials and methods

3.1 Waste resources

Waste resources used in the present experiment are described in Table 1.

Table 1. Description of waste resources

Waste resource	Short name	Description
Bottom wood ash	BWA	Biomass ash originating in a district heating system with a grate fired boiler of the company Akershus Energi AS, which is located in Årnes, Norway, (63°96'N, 10°23'E). Parent material is timber that is unfeasible for industrial use and residues from the local mill. Both sources are clean of or have a low content of heavy metals.
MBM (Mosvik)	Mosvik	Stabilised, sanitised and pelletized MBM originating in the slaughterhouse in Mosvik, Norway (63°82'N, 11°01'E).
MBM (Hamar)	Hamar	Stabilised and sanitised MBM originating in the slaughterhouse in Ingeberg, Hamar (60°84'N, 11°10'E), Norway.
Composted catering waste	CCW	Parent material is source-separated catering waste originating in Rica Sunnfjord Hotel, Førde, Norway (61°45'N, 5°86'E). After separation of fat and water, protein and carbohydrate-rich organic waste was treated in a reactor developed by the company Global Enviro AS.
Composted fish sludge	CFS	Parent material is a mixture of feed residues and excrements from a cod hatchery of Fjord Gadus (Codfarmers ASA). The sludge was first dewatered and then treated in similar reactor as CCW.
Ekogödsel 8353	Eko 8353	Stabilised, sanitised and pelletized MBM (N and P) combined with vinasse (N and K) gives an end product with an N:P:K:S ratio of 8:3:5:3.
Ekogödsel Plus 6383	Eko 6383	Stabilised, sanitised and pelletized MBM (N and P) combined with vinasse (N and K) gives an end product with an N:P:K:S ratio of 6:3:8:3.

Table 2 is the description or chemical characteristics of all of the waste resources. 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/NO_3-N and NH_4-N were determined after extraction with 2 M KCl (Henriksen & Selmer-Olsen 1970; Selmer-Olsen 1971). To determine 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).

All of the materials had dry matter contents > 85 % making them suitable for transportation.

BWA was with pH 13 rather alkaline, but it contained far less Ca than the BWA, which we had used as K fertiliser in combination with MBM during a previous growth experiment with spring cereals (Haraldsen et al. 2011b). BWA used in the present experiment contained also appreciable K amounts and had a favourable Ca:K ratio of 2. We assumed therefore that the pH increase would be low enough to allow annual application of BWA. Moreover, BWA contained 1.3 g $(100g)^{-1}$ P, but only 11% of it was directly available to plants according to P-AL analysis.

All of the MBM products (Mosvik, Hamar, Eko 8353 and Eko 6383) contained substantial amounts of N (7.7-9%), whereof almost everything was present as organic N. Mosvik had somewhat higher total N contents than the other MBMs included in the experiment. Eko 8353 had somewhat lower N content and Eko 6383 somewhat higher N content than indicated by declaration. All MBM products contained moreover considerable amounts of P, resulting in narrow N:P ratios of 1.6-2. In Norway it is recommended to supply spring cereals with N and P equivalent to N:P ratios of 6-7.5 (Bioforsk 2003). According to P-AL analyses only half of P in the different MBM products was directly available to plants. However, N:P-AL ratios were still as narrow as 3.2-4.5. Whereas K contents were negligible in Norwegian MBM products, the Swedish products Eko 8353 and Eko 6383 contained respectively 3.9 and 4.8 % K, which was directly available according to K-AL analyses. Swedish MBM products contained moreover 2.1 and 2.6% S.

CCW had the highest TOC content among all waste resources but the lowest total N content resulting in a C:N ratio of 10.9. Compared to conventional composts based on source-separated household waste, this ratio is still rather narrow and allowed the assumption that N in CCW was more available than in conventional composts (Bøen & Haraldsen 2011). In comparison to the other waste resources CCW contained rather small amounts of P resulting in an N:P ratio of 9.4. There was somewhat more K in compost than in MBM, but K-AL contents were lower than in Swedish MBM products.

CFS was in its chemical composition similar to Norwegian MBM products. The total N content of CFS was as high as 7.7%, whereof most was present as organic N. However, compared to all other N-rich waste resources CFS contained the highest amount of mineral N with 3% of total N. The total P content of CFS was lower than in MBM products but 68% of P was directly available to plants according to P-AL analyses, resulting in an N:P ratio of 3.5 and N:P-AL of 5.1. Also K-AL, Mg-AL and S contents were as low as in Norwegian MBM, but Ca-AL contents were somewhat lower than in MBM.

Table 2. Chemical characteristics of bottom wood ash (BWA), MBM Mosvik (Mosvik), MBM Hamar (Hamar), composted catering waste (CCW), composted fish sludge (CFS), Ekogjödsel 8353 (Eko 8353) and Ekogjödsel 6383 (Eko 6383)

Para-meter	Unit	BWA	Mosvik	Hamar	CCW	CFS	Eko 8353	Eko 6383
pH		13	6.5	6.5	5.2	5.9		
EC	mS m^{-1}	1200	110	340	440	570	1000	1100
DM	g $(100g)^{-1}$	100	98	97	92	87	94	94
Loss on ignition	g $(100g)^{-1}$ DM	0.3	71	67	92	83	60	59
TOC	g $(100g)^{-1}$ DM	0.2	41.2	38.9	53.4	48.1	34.8	34.2
Total N	g $(100g)^{-1}$ DM	<0.1	9	8.2	4.9	7.7	7.9	7.7
C:N ratio			4.6	4.7	10.9	6.3	4.4	4.4
NH_4-N	g $(100g)^{-1}$ DM	0.00045	0.031	0.0414	0.021	0.26	0.049	0.0482
NO_3-N	g $(100g)^{-1}$ DM	0.00285	<0.0003	<0.0002	<0.0002	<0.0002	<0.0002	<0.0001
Total P	g $(100g)^{-1}$ DM	1.3	4.5	5.2	0.52	2.2	4.3	4.1
P-AL	g $(100g)^{-1}$ DM	0.14	2	2.6	0.31	1.5	2	2.1
N:P			2	1.6	9.4	3.5	1.8	1.9
N:P-AL			4.5	3.2	15.8	5.1	4.0	3.7
K-AL	g $(100g)^{-1}$ DM	7	0.27	0.45	0.76	0.13	3.9	4.8
Mg-AL	g $(100g)^{-1}$ DM	1.3	0.11	0.18	0.092	0.49	0.1	0.1
Ca	g $(100g)^{-1}$ DM	14	10	12	1.3	5.3	10	11
Ca-AL	g $(100g)^{-1}$ DM	9.2	4.2	5.4	0.98	3.7	4.7	5.4
S	g $(100g)^{-1}$ DM	0.07	0.96	0.71	0.23	0.46	2.1	2.6

According to heavy metal concentrations in the waste materials (Table 3) all of the waste resources could be applied as fertiliser to agricultural land in Norway. Mosvik, Hamar, CCW, CFS, Eko 8353 and Eko 6383 could be categorised into quality class 0 according to Norwegian regulations (Norwegian Ministry of Agriculture 2003). Material of quality class 0 can be applied to agricultural land without restrictions despite the crops' needs. BWA could be categorised into quality class I due to elevated Cd, Cr and Zn contents. The use of quality class I material is restricted to 40 t DM ha^{-1} 10 yr^{-1}.

Table 3. Heavy metal contents in bottom wood ash (BWA), MBM Mosvik (Mosvik), MBM Hamar (Hamar), composted catering waste (CCW), composted fish sludge (CFS), Ekogödsel 8353 (Eko 8353) and Ekogödsel 6383 (Eko 6383)

Para-meter	Unit	BWA	Mosvik	Hamar	CCW	CFS	Eko 8353	Eko 6383
Cd	mg kg^{-1} DM	0.45^{I}	0.02^{0}	0.01^{0}	0.01^{0}	0.17^{0}	0.01^{0}	0.01^{0}
Cr	mg kg^{-1} DM	18^{0}	1.6^{0}	1.3^{0}	0.5^{0}	2.1^{0}	1.8^{0}	1.2^{0}
Cu	mg kg^{-1} DM	65^{I}	8.7^{0}	8^{0}	10^{0}	16^{0}	5.8^{0}	6^{0}
Hg	mg kg^{-1} DM	$<0.001^{0}$	0.006^{0}	0.001^{0}	0.011^{0}	0.037^{0}		
Ni	mg kg^{-1} DM	15^{0}	1.8^{0}	1.7^{0}	2.1^{0}	2.4^{0}	2.5^{0}	1.3^{0}
Pb	mg kg^{-1} DM	3.3^{0}	1.1^{0}	$<0.31^{0}$	$<0.33^{0}$	0.65^{0}	$<0.32^{0}$	$<0.33^{0}$
Zn	mg kg^{-1} DM	220^{I}	99^{0}	91^{0}	36^{0}	290^{0}	75^{0}	80^{0}

^{0} Quality class 0, ^{I} Quality class I

3.2 Experimental soil

The experimental soil was a 9:1 blend of Elverum sand and sphagnum peat. For ratio of particle size in Elverum sand see Table 4. Elverum sand was chosen as it contains low amounts of plant-available nutrients (Table 5). Fertiliser treatments were therefore expected to show clear effects. Elverum sand had previously been used for growth experiments with organic waste resources by Jeng et al. (2004; 2006) and Haraldsen et al. (2011a, b). We added 10% of peat to decrease soil density and to improve the water holding capacity of the sand. Peat is rather acidic. In order to keep soil acidity at around pH 6.5, we applied 0.53 g $CaCO_3$ L^{-1} to the soil mixture. Analyses of soil samples, which were taken after the experiment was finished in 2011, showed that pH was on average somewhat higher than originally intended.

Table 4. Particle size distribution in Elverum sand

Gravel	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	Clay
> 2 mm	2-0.6 mm	0.6-0.2 Mm	0.2-0.06 mm	0.06-0.02 mm	0.02-0.006 mm	0.006-0.002 mm	<0.002 mm
0.4 %[1]	0.6 %	61.7 %	34.3 %	1.4 %	0.0 %	1.0 %	1.0 %

[1] Ratio of total sample

Table 5. Chemical characteristics of Elverum sand before liming, measured in 2003

	pH	TOC	Total N	P-AL	K-AL	Mg-AL	Ca-AL	Na-AL
mg 100 g^{-1}	6.6	< 100	< 50	2.2	4.5	1.7	11.9	1.4
mg 100 cm^{-3} [a]		130	65	2.9	5.9	2.2	15.5	1.8

[a] Values are corrected for soil density (1.3 g cm^{-3}). TOC=total organic carbon, AL=extraction with ammonium lactate + acetic acid

3.3 Experimental design and setup

The experiment was conducted in a greenhouse located at the Norwegian University of Life Sciences in Ås (59°67'N, 10°77E). Kick/Brauckman pots (7.5 L with a top diameter of 21.5 cm) were located randomised side by side on a table. The pots were filled with experimental soil before fertiliser treatments were equally blended into the upper 5 cm.

Fertiliser treatments were designed to supply crops with N, P and K similar to that supplied by compound fertiliser Yara Fullgjødsel® 22–3–10. All of the four N-rich waste resources (Mosvik, Hamar, CCW and CFS) were tested alone and in combination with K-rich BWA. Fertiliser treatments were compared with two merchandised organic compound fertilisers that are based on MBM and vinasse (Eko 8353 and Eko 6383), mineral compound fertiliser Yara Fullgjødsel® (minNPK) and an unfertilised control treatment. Additionally we had a treatment with only calcium nitrate (minN) to test the soil's ability to supply plants with P and K. Also we tested the fertilisation effect of only BWA and the treatment minN+BWA was included to test the fertilisation effect of BWA at optimal N supply.

Each of the treatments was tested at two fertiliser levels, 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. The levels were set to equal 80 kg N ha^{-1} + 35 kg K ha^{-1} and 160 kg N ha^{-1} + 70 kg K ha^{-1}. Fertiliser levels were adapted to Norwegian fertiliser recommendations for an expected yield of respectively 3 and 8 t ha^{-1} for barley and 2.5 and 7.5 t ha^{-1} for wheat (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 of the treatments. For the experimental design see Table 6.

Barley (Tyra) was sown 15 July 2010 and harvested 6 and 7 October 2010, 83-84 days after sowing. The pots stayed in the greenhouse during autumn. Before wheat (Bastian) was sown 3 February 2011, the soil surface with remaining plant stubbles was scratched imitating harrowing and fertiliser was mixed into the upper 5 cm. Wheat was harvested 15 April 2011, 71 days after sowing. During both years there were sown 30 seeds per pot and after germination the weakest plants were removed, leaving 20 plants per pot. Harvesting was done at ripeness by shearing all straws in each pot at approximately 5 cm above soil surface. Harvested plant biomass was dried at 40°C for 2 days before grains were threshed and grains and straw were weighed separately. 10 days after wheat harvest, soil samples from all of treatments were taken (0-20 cm). Soil pH, Ca-AL, K-AL, Mg-AL, Na-AL, P-AL, NO_2/NO_3-N and NH_4-N were determined as described.

The intended temperature in the greenhouse was 20°C during the day (16 h) and 15°C during the night (8 h). However, during the barley experiment in 2010 inside temperature in the greenhouse exceeded outside temperature during warm days and reached up to 30°C during some days.

The plants were irrigated three times a week. Each pot was watered up at the beginning of the experiment and then 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.

In July 2010 at Zadoks 13-14 (Zadoks et al. 1974) of barley, the soil was watered up to saturation and given a surplus of 28 mm m^{-2}, simulating heavy pre-summer rain. The leaching water was collected in 1 L plastic bottles and analysed for total N (Kjeldahl N, NS 4743 1993), NO_3- and NO_2-N (ISO 13395 1996), as well as total P (ISO 6878 2004).

In July 2010, barley was accidently not irrigated for 6 days just after the leaching episode and insufficiently for 1 week thereafter.

Table 6. Amount of waste resources applied and respective contents of mineral N, total P, P-AL and total K/K-AL (kg ha^{-1})

	80 kg N ha^{-1} + 35 kg K ha^{-1}					160 kg N ha^{-1} + 70 kg K ha^{-1}				
	Amount kg ha^{-1}	N_{min} kg ha^{-1}	P kg ha^{-1}	P-AL kg ha^{-1}	K/ K-AL[a] kg ha^{-1}	Amount kg ha^{-1}	N_{min} kg ha^{-1}	P kg ha^{-1}	P-AL kg ha^{-1}	K/ K-AL[a] kg ha^{-1}
Control	0	0	0	0	0	0	0	0	0	0
BWA	461	0	6	1	35	921	0	12	1	70
minNPK	370	80	10	10	36	741	160	21	21	73
minN	516	80	0	0	0	1032	160	0	0	0
minN+BWA	516	80	6	1	35	1032	160	12	1	70
Mosvik	907	0.3	40	18	2	1814	0.6	80	36	5
Mosvik+BWA	1368	0.3	46	18	37	2735	0.6	92	37	75
Hamar	1006	0.4	51	25	4	2012	0.8	101	51	9
Hamar+BWA	1466	0.4	57	26	39	2933	0.8	113	52	79
CCW	1775	0.3	8	5	12	3549	0.7	17	10	25
CCW+BWA	2235	0.3	14	6	47	4470	0.7	29	11	95
CFS	1194	2.7	23	16	1	2388	5.4	46	31	3
CFS+ BWA	1655	2.7	29	16	36	3309	5.4	58	32	73
Eko 8353	1077	0.5	44	20	39	2155	1.0	87	41	79
Eko 6383	1105	0.5	43	22	50	2211	1.0	85	44	100

[a] K in BWA is calculated based on total K in the material, K in other material is calculated based on analyses of K-AL.

3.4 Data analysis

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

Where
NUE= Nutrient use efficiency
N_{up} = N uptake in grain (kg ha^{-1})
$N_{applied}$ = Total N amount applied with fertiliser treatment

Mineral fertiliser equivalent (MFE %, Delin 2011), which is defined as the rate of waste resource with the same effect as minNPK on biomass production or N uptake, was calculated as presented in Figure 1. Total biomass production and N uptake after minNPK application were plotted against fertilizer rates (0, 80,160 kg N ha^{-1}) and minimum least squares were fitted to the values to obtain corresponding mineral fertiliser rates for all N-rich waste resources. MFE (%) were expressed by dividing the corresponding mineral fertiliser rate by the amount of total N applied (80 or 160 kg N ha^{-1}).

Equivalent to NUE (%), phosphorus use efficiency (PUE %) was calculated for BWA during 2011, and MFE (%) on P uptake was calculated for minN+BWA (2011) by dividing the corresponding mineral fertiliser rate by the amount of P applied with BWA (6 and 12 kg P ha^{-1}).

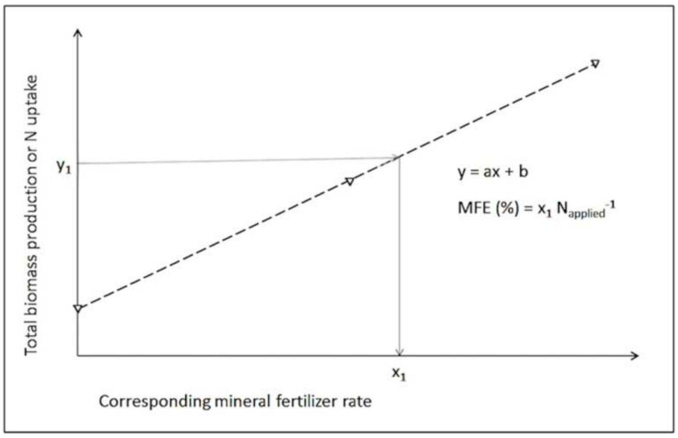

Figure 1. Calculation of mineral fertiliser equivalent (MFE %), where the respective corresponding mineral N fertiliser rate (x_1) of each N-rich waste is calculated by the function describing total biomass production or N uptake as effect of different minNPK rates. N applied is the total N amount applied with the fertiliser treatment (modified after Delin, 2011)

Total P- and K-balances in the soil were calculated as follows:

P, K balance = (P, K residues +) applied P, K – P, K uptake in aboveground biomass(- leached P, K)

Supply of K from reserve-K (defined as soil-K release from K not originating in K-AL, Øgaard et al. 2001) was calculated as follows:

Reserve-K = K uptake in aboveground biomass – applied K – K-AL change

One-way analysis of variance (ANOVA) was carried out where all treatments were included. Nutrient utilisation in response to fertilizer application was analysed as nutrient uptake (kg

ha^{-1}) by multiplying concentration of the pooled samples with the yield of each replication. For multiple comparisons between treatments the Tukey's studentized range test was applied with a significance level of *P*= 0.05. The program package SAS/STAT (SAS Institute Inc. 1989) was used for the statistical analysis.

4. Results

4.1 Grain and straw yield

Barley 2010

During 2010, all organic waste resources resulted in equally high grain yield as minNPK at fertiliser rate 80 kg N ha^{-1} (Figure 2), with MFE (%) on grain yield varying between 59-90% (Table 7). At fertiliser rate 160 kg N ha^{-1} Mosvik, Mosvik+BWA, Hamar, CCW and CFS resulted in equally high grain yield as minNPK. Straw yield was significantly lower after fertilisation with all waste resources than with minNPK at both fertiliser rates. MFE (%) on grain yield tended therefore to be higher than MFE (%) on total yield.

MinN treatments with and without BWA resulted in equally high grain yields as the organic waste resources. Straw production after minN fertilisation of both fertiliser amounts was equally high as after fertilisation with 80 kg N ha^{-1} minNPK, and straw production after minN+BWA fertilisation of both fertiliser amounts was equally high as after fertilisation with 160 kg N ha^{-1} minNPK.

Application of only BWA resulted in equally low grain and straw yield as the unfertilised control and there were no significant effects of BWA in combination with organic waste resources or minN on grain or straw yield at any fertiliser rate.

Higher fertiliser rates tended overall to result in higher biomass production, but differences between fertiliser rates on grain yield were only significant for minNPK. MinNPK, CCW+BWA and Eko 6383 resulted in significantly higher straw production after application of 160 compared to 80 kg N ha^{-1}.

Wheat 2011

During 2011, 160 kg N ha^{-1} minNPK resulted in clearly higher grain yield than the year before, and in significantly higher grain yield than all other treatments (Figure 2). Also at fertiliser rate 80 kg N ha^{-1} minNPK tended to result in higher grain yield than the organic waste resources, but Hamar, CCW+BWA, CFS, CFS+BWA and Eko 8353 resulted in equally high grain yield. MFE (%) on grain yield varied between 44-60% at fertiliser rate 160 kg N ha^{-1} and between 31-82% at fertiliser rate 80 kg N ha^{-1} (Table 8). MinNPK resulted in the highest straw yield among all treatments at both fertiliser rates, and as during 2010 MFE (%) on grain yield tended to be higher than MFE (%) on total yield.

After fertilisation with organic waste resources grain yields were generally equally high during 2011 as during 2010. Straw yield in response to fertilisation with organic waste resources seemed to be somewhat lower during 2011 than during 2010.

There was a clear effect of BWA, when comparing the effects of minN treatments with and without BWA. MinN treatments of both fertiliser rates resulted in equally low grain and straw yields as the unfertilised control, whereas minN+BWA resulted in equally high grain and straw yield as organic waste resources at the same fertiliser rate. Also during 2011, BWA alone resulted in equally low grain and straw yields as the unfertilised control.

Grain and straw yield increased significantly after fertilisation 160 kg N ha^{-1} compared to 80 kg N ha^{-1} for all treatments except Mosvik+BWA, CFS and Eko 6383. Crops tended, however, to respond stronger to double fertiliser rates for minNPK fertiliser compared to the organic waste resources.

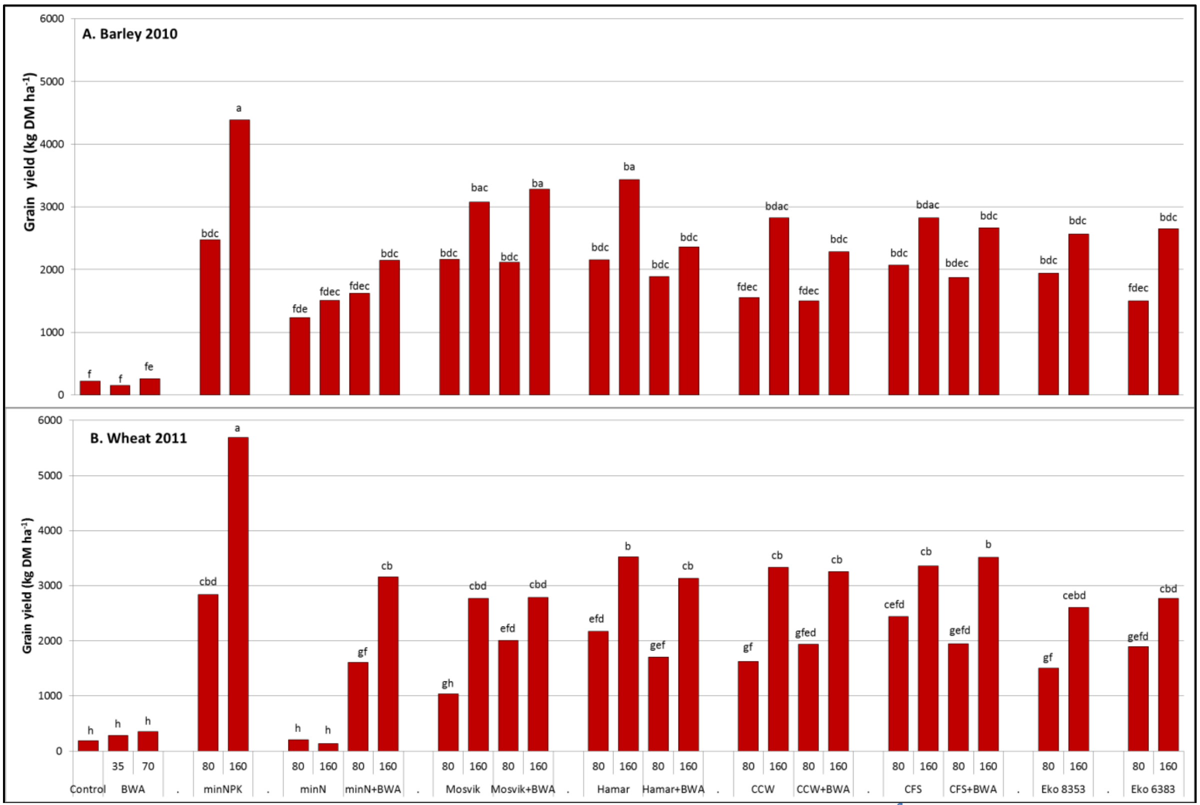

Figure 2. Effect of fertiliser treatments on grain of barley and wheat (kg DM ha^{-1}). Letters refer to Tukey's test (one-way ANOVA model including all treatments).

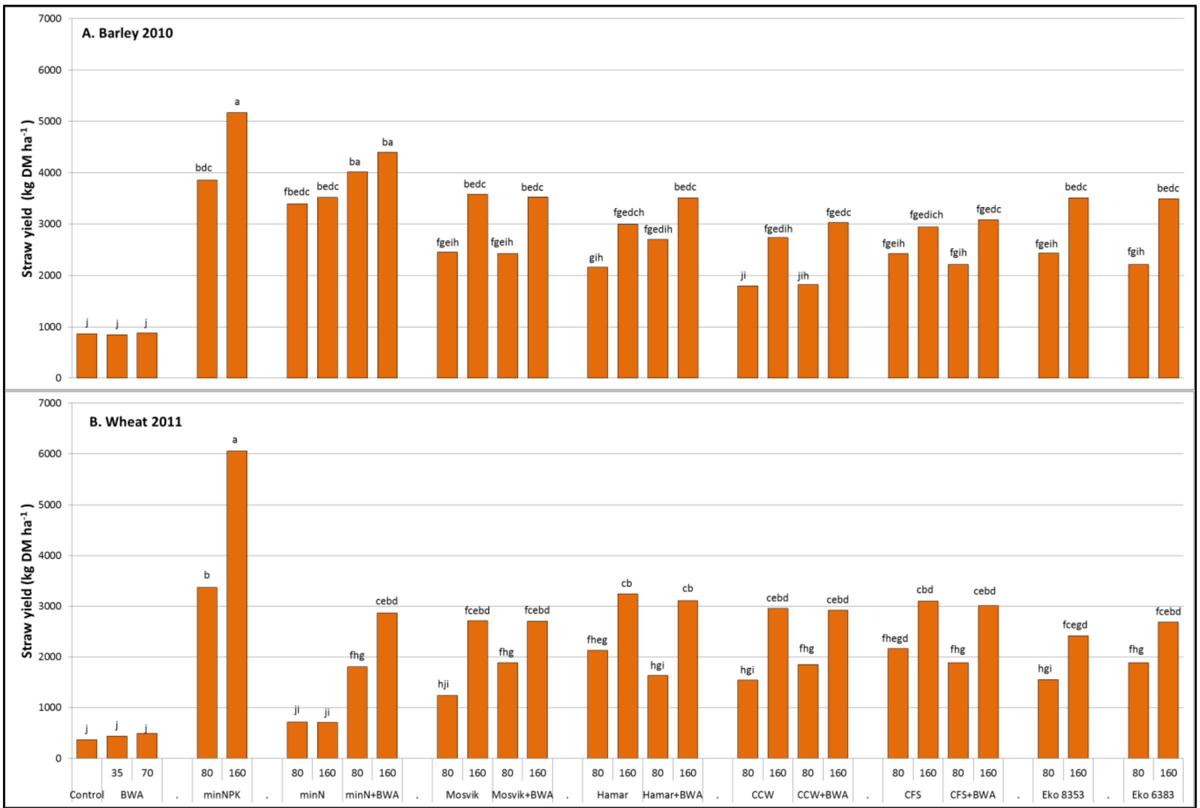

Figure 3. Effect of fertiliser treatments on straw yield of barley and wheat (kg DM ha^{-1}).). Letters refer to Tukey's test (one-way ANOVA model including all treatments).

4.2 N uptake, leaching and residues in soil

Barley 2010

During 2010, N uptake in grain was equally high after fertilisation with minNPK and organic waste resources at both fertiliser rates (Figure 4), with MFE (%) on N uptake in grain varying between 64-118% (Table 7). At fertiliser rate 80 kg N ha^{-1}, between 25-42% of N applied with organic waste resources was taken up in grains (NUE %), whereas NUE % of minNPK was 45%. Only Hamar and CCW resulted in significantly higher N uptake in grain after fertilisation of 160 kg N ha^{-1} compared to 80 kg N ha^{-1}. At fertiliser rate 160 kg N ha^{-1}, between 24-35% of N applied with organic waste resources was taken up in grains (NUE %), whereas NUE % of minNPK was 32%. N uptake in straw was higher after fertilisation with minNPK compared to organic waste resources (results are not shown), and MFE (%) on total N uptake tended therefore to be lower than MFE (%) on N uptake in grain.

MinN treatments tended to result in lower N uptake in grain compared to all other N-rich treatments. The leaching episode at Zadoks 13-14 resulted in very high N losses (65 kg NO_3 ha^{-1}) after fertilisation with 160 kg N ha^{-1} minN (Figure 4). Also 160 kg N ha^{-1} minN+BWA resulted in considerable leaching losses, but combination of minN with BWA reduced losses to 32 kg N ha^{-1}.

Also after fertilisation with minNPK we found significant amounts of N in the leaching water, but only 11 kg NO_3 ha^{-1} were lost after fertilisation with 160 kg N ha^{-1} minNPK. After application of organic waste resources N leaching losses were as low as after the unfertilised control.

Wheat 2011

During 2011, the highest fertiliser rate of minNPK resulted in the highest N uptake in grain (Figure 5), and 63% (NUE %, Figure 5) of N applied with 160 kg N ha^{-1} minNPK was taken up in grains.

All organic waste resources resulted in significantly lower N uptake in wheat grain than respective fertiliser rates of minNPK, with MFE (%) on N uptake in grain varying between 27-60% (Table 8). At fertiliser rate 80 kg N ha^{-1} between 14-35% of N applied with organic fertilisers was taken up in grains. Higher fertiliser rates of organic waste resources resulted in significantly higher N uptake than lower rates, with the exception of Mosvik+BWA and Eko 6383, and between 22-35 % of N applied with waste resources was taken up in grains at fertiliser rate 160 kg N ha^{-1}. MBM products (Mosvik, Hamar, Eko 8353 and Eko 6383) resulted in clearly lower N uptake than during 2010, whereas CCW and CFS resulted in approximately equally high N uptake during both years.

MinN treatments without BWA resulted in equally low N uptake in grain as the unfertilised control and BWA. MinN+BWA on the other hand resulted in equally high N uptake in grain as minNPK at fertiliser rate 80 kg N ha^{-1} and in significantly higher N uptake than all organic waste resources at fertiliser rate 160 kg N ha^{-1}.

Analyses of soil samples showed that there were 56 kg N ha^{-1} left in the soil after fertilisation with 160 kg N ha^{-1} minN. After application of 80 kg N ha^{-1} minN, 12 kg N ha^{-1} were left at the day of wheat harvest. NO_3 residues in the soil were significantly higher after fertilisation with minN than after respective fertiliser rates of all other treatments. 10 days after wheat harvest up to 5.6 kg N ha^{-1} were present as mineral N after fertilisation with organic waste resources (160 kg N ha^{-1} CFS+BWA). However, there were no significant differences in total N residues in the soil between unfertilised control, organic waste treatments, minNPK treatments and minN+BWA treatments.

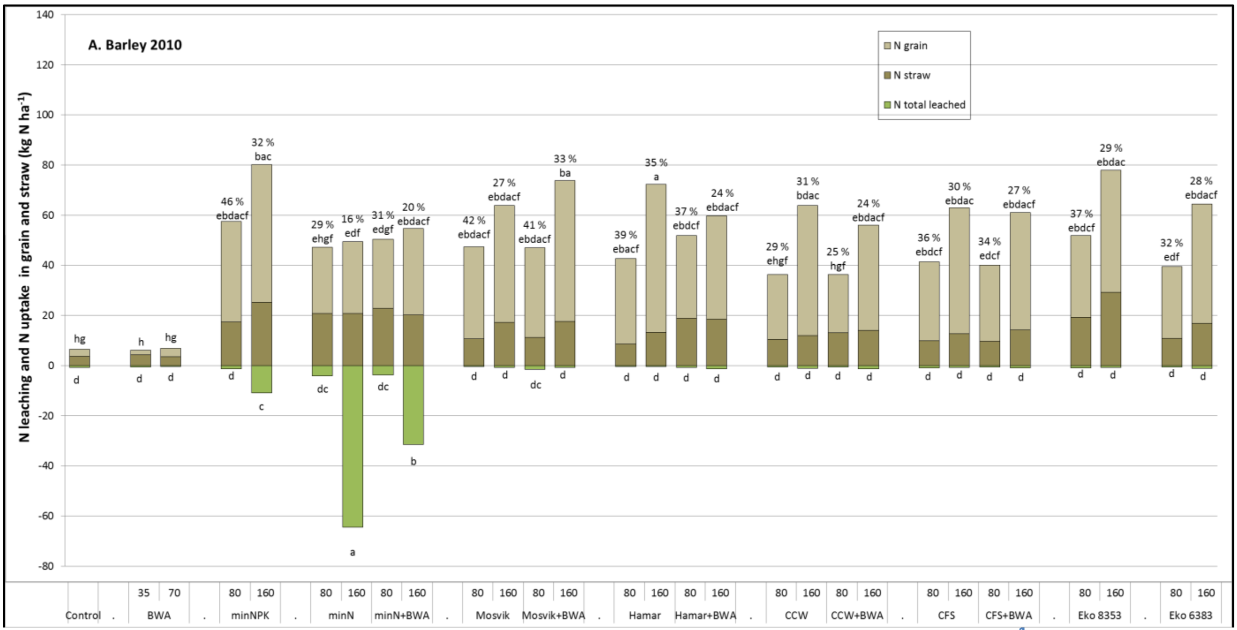

Figure 4. Effects of fertiliser treatments on N uptake in grain and straw of barley (kg N ha^{-1}), and total N leaching losses. Percentages refer to NUE (%) in grain, letters refer to Tukey's test (one-way ANOVA including all treatments) on N uptake in grain. Treatments with the same letter are not significantly different regarding N uptake in grain.

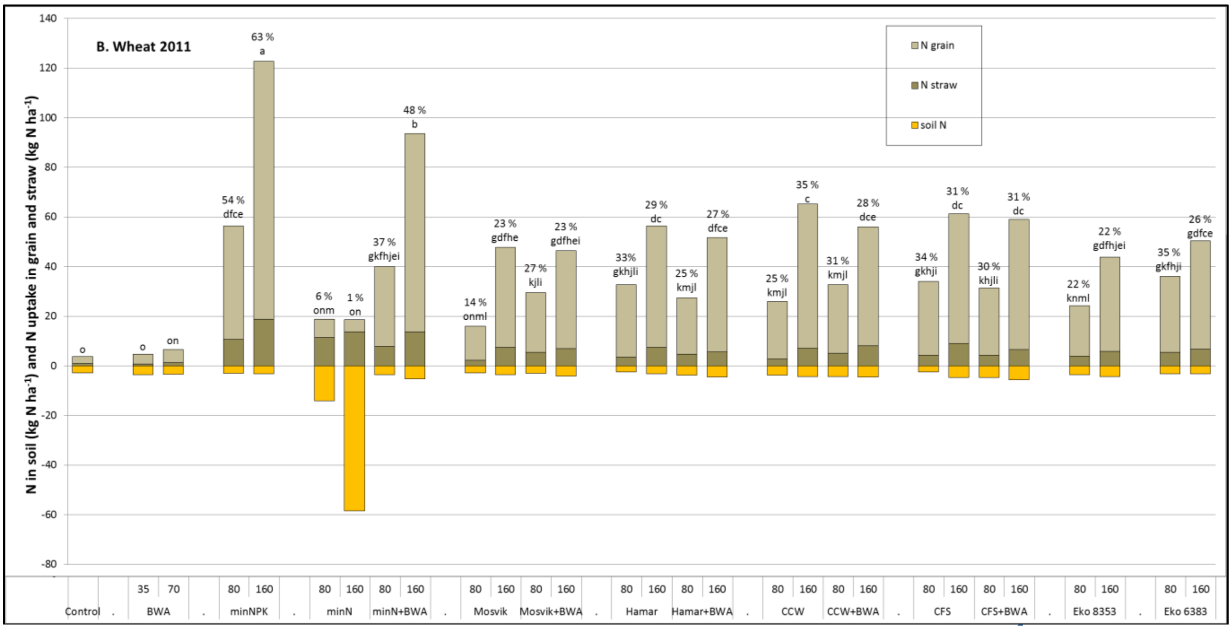

Figure 5. Effects of fertiliser treatments on N uptake in grain and straw of wheat (kg N ha^{-1}), and mineral N residues at the end of the experiment. Percentages refer to NUE (%) in grain, letters refer to Tukey's test (one-way ANOVA model including all treatments) on N uptake in grain. Treatments with the same letters are not significantly different regarding N uptake in grain.

Table 7. MFE (%) on grain and total yield as well as on N uptake in grain and total N uptake for barley 2010

	Amount applied 80 kg N ha^{-1} + 35 kg K ha^{-1}				Amount applied 160 kg N ha^{-1} + 70 kg K ha^{-1}			
	MFE % (grain yield)	MFE % (total yield)	MFE % (N uptake in grain)	MFE % (total N uptake)	MFE % (grain yield)	MFE % (total yield)	MFE % (N uptake in grain)	MFE % (total N uptake)
Mosvik	90	76	118	100	67	62	78	73
Mosvik + BWA	88	74	114	99	72	64	97	87
Hamar	90	68	107	87	76	59	103	85
Hamar + BWA	77	75	103	113	50	53	67	67
CCW	61	46	75	69	61	49	88	73
CCW + BWA	59	45	64	69	48	46	69	62
CFS	86	73	97	84	61	51	85	72
CFS + BWA	77	63	92	80	57	51	78	69
Eko 8353	80	70	101	113	55	55	82	93
Eko 6383	59	54	86	79	57	56	80	74

Table 8. MFE (%) on grain and total yield as well as on N uptake in grain and total N uptake for wheat 2011

	Amount applied 80 kg N ha^{-1} + 35 kg K ha^{-1}				Amount applied 160 kg N ha^{-1} + 70 kg K ha^{-1}			
	MFE % (grain yield)	MFE % (total yield)	MFE % (N uptake in grain)	MFE % (total N uptake)	MFE % (grain yield)	MFE % (total yield)	MFE % (N uptake in grain)	MFE % (total N uptake)
Mosvik	31	30	27	24	47	44	40	39
Mosvik + BWA	66	62	47	47	47	44	39	38
Hamar	72	67	57	53	60	55	48	46
Hamar + BWA	55	49	45	44	53	51	45	42
CCW	52	46	45	41	57	51	58	54
CCW + BWA	64	57	54	53	55	50	47	46
CFS	82	72	59	55	57	53	52	50
CFS + BWA	64	58	53	50	60	53	52	49
Eko 8353	48	44	40	39	44	40	38	36
Eko 6383	62	57	60	58	47	44	43	41

4.3 P uptake, leaching and residues in soil

Barley 2010

During 2010, organic waste resources resulted in equally high P uptake in grain as respective amounts of minNPK at both fertiliser rates (Table 12).

Application of 160 kg N ha^{-1} minN resulted in significantly lower P uptake in grain than minNPK. Differences in P uptake between minNPK and minN (160 kg N ha^{-1}) were not significant after combination of minN with BWA. BWA did not have an increasing effect on P uptake in grain in combination with any of the organic waste resources at fertiliser rates, and BWA alone resulted in equally low P uptake as the unfertilised control.

P losses as result of the leaching episode during Zadoks 13-14 were all in all negligible (results are not shown). The highest P loss was found in the leaching water of the unfertilised control treatment. Lost P was positively correlated to lost TOC in the leaching water (results are not shown, R^2=0.76). P loss after the unfertilised control was significantly different from P loss after the highest amount of minN, otherwise there were no significant differences between P contents in leaching water of the different treatments.

Calculated soil-P balances after barley harvest show that all treatments apart from the unfertilised control and minN, which did not receive any P fertilisation, supplied more P than the amount plants could utilise (Table 9). P surplus was always higher after application of BWA compared to the respective treatment without BWA.

Wheat 2011

During 2011, 160 kg N ha^{-1} minNPK resulted in the highest P uptake in grain at the same level as Hamar, Hamar+BWA, CCW+BWA, CFS and CFS+BWA (Table 12).

At fertiliser rate 80 kg N ha^{-1} all waste resources resulted in equally high P uptake in grain as minNPK with the exception of Mosvik, Eko 8353 and Eko 6383. 80 kg N ha^{-1} Mosvik resulted in equally low P uptake in grain as the unfertilised control, and both Eko 8353 and Eko 6383 resulted in significantly lower P uptake in grain than minNPK. After fertilisation with Mosvik, Eko 8353 and Eko 6383, the amount of plant-available P measured as P-AL in the soil was equally low as in the unfertilised control soil after wheat harvest (Table 13). P uptake in grain increased significantly after application of the doubled fertiliser rate of Mosvik, and P uptake in grain after fertilisation with Hamar and Mosvik was equally good in combination with BWA at both fertiliser rates. Also, P-AL pools in the soil increased significantly after fertilisation with 160 kg N ha^{-1} Mosvik+BWA and Hamar+BWA compared with the unfertilised control. P-AL contents in the soil can be considered as moderately high after these treatments according to fertiliser recommendations in Norway, even though original P-AL values in the experimental soil were low (Bioforsk 2003). Application of the doubled fertiliser rate of Eko 8353 and Eko 6383 significantly increased P uptake in grain, which, however, was still significantly different from P uptake in grain after fertilisation with minNPK of the same fertiliser rate.

Both fertiliser rates of minN resulted in equally low P uptake in grain as the unfertilised control, but BWA had a significantly increasing effect on P uptake in grain after fertilisation with minN for both rates in comparison to fertilisation with minN alone. MinN+BWA took up 2.9 and 4.5 kg P ha^{-1} more than respectively 80 kg N ha^{-1} and 160 kg N ha^{-1} minN. Hence, 48.2 and 37.3% of P in BWA could be utilised after application in combination with minN (PUE %, Table 10). According to MFE (%) on P uptake BWA could compensate for 91.1% and 73.3% of P applied with minNPK after application in combination with respectively 80 and 160 kg N ha^{-1} minN. BWA alone, on the other hand, resulted only in uptake of 1.4 and 1.6 kg P ha^{-1} after fertilisation with 35 kg K ha^{-1} and 70 kg K ha^{-1}. MFE (%) of BWA alone was with 12.2-17.0% therefore clearly lower than after fertilisation of BWA in combination with minN.

Fertilisation with BWA, minNPK, minN, minN + BWA, CCW, CCW + BWA at both fertiliser rates and 80 kg N ha^{-1} CFS tended to decrease the amount of plant-available P measured as P-AL in comparison to initial values in the experimental soil. Still, total P pools increased after all treatments except for minN of both loads and the unfertilised control (Table 9).

Table 9. P balances and effect of fertiliser treatments on readily available P (P-AL) as kg P ha^{-1} after wheat harvest

	80 kg N ha^{-1}			160 kg ha^{-1}		
	Total P balances		P-AL change	Total P balances		P-AL change
	Barley	Wheat		Barley	Wheat	
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Control	-2	-3	-16			
BWA	5	9	-11	10	20	-10
minNPK	2	7	-20	9	20	-16
minN	-4	-5	-21	-5	-6	-17
minN + BWA	-1	2	-18	4	11	-15
Mosvik	32	70	0	69	143	28
Mosvik + BWA	37	79	35	79	163	185
Hamar	42	87	43	88	181	50
Hamar + BWA	49	101	52	103	209	140
CCW	2	7	-22	6	17	-22
CCW + BWA	8	18	-3	18	38	-9
CFS	14	30	-2	34	70	26
CFS + BWA	20	44	19	45	93	52
Eko 8353	36	77	9	78	159	69
Eko 6383	36	76	28	74	154	68

Table 10. PUE (%) and MFE (%) on P uptake in wheat after BWA fertilisation

		P fertilised	P uptake (grain and straw)	P uptake – P uptake (minN)	PUE	MFE on P uptake
		kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%	%
BWA	35 kg K ha^{-1}	6	1.4	1.0	15.5	17.0
	70 kg K ha^{-1}	12	1.6	1.1	9.2	12.2
minN+BWA	80 kg N ha^{-1}	6	3.4	2.9	48.2	91.1
	160 kg N ha^{-1}	12	4.9	4.5	37.3	73.3
minNPK	80 kg N ha^{-1}	10	5.9	5.4	52.2	110.2
	160 kg N ha^{-1}	21	10.1	9.7	46.6	98.0

4.4 K uptake, leaching and residues in soil

Barley 2010

During 2010, more K than N was removed by grain and straw after all fertiliser treatments. After fertilisation with 80 and 160 kg N ha^{-1} minN plants removed respectively 150 and 115 kg K ha^{-1} with aboveground biomass. This means that plants took up 3 and 2 times as much K as N, even though there was not applied any K with minN.

At fertiliser rate 80 kg N ha^{-1} organic waste resources resulted in equally high K uptake in grain and straw as minNPK at the same fertiliser rate with the exception of CCW and Eko 6383. 160 kg N ha^{-1} minNPK resulted in the highest K uptake in grain and straw among all treatments, but there were no significant differences to K uptake in grain and straw by 80 kg N ha^{-1} minN, 80 and 160 kg N ha^{-1} minN+BWA and Hamar+BWA at both fertiliser rates.

There was no significant effect of BWA on K uptake in grain and straw in combination with minN at any fertilisation rate, but BWA resulted in increased K uptake in aboveground biomass after combination with Hamar at both fertiliser rates. Application of BWA alone resulted in equally low K uptake in grain and straw as the unfertilised control.

The highest K leaching losses were found after fertilisation with 160 kg N ha^{-1} minN and minN+BWA. There were collected 15 kg K ha^{-1} in the leaching water after fertilisation with 160 kg N ha^{-1} minN, even though there was not applied any K with the fertiliser treatment. There was a positive correlation between K leaching losses and total N leaching losses (results are not shown, R^2=0.37).

Total K balances of the barley experiment in 2010 show that all of the plants took up more K than applied with the fertiliser except for BWA and 160 kg N ha^{-1} Eko 6383. Application of BWA always seemed to somewhat reduce the decline of K resources in the soil. Only after fertilisation with 80 kg N ha^{-1} Hamar, total soil K reserves decreased despite BWA application.

Wheat 2011

During 2011, total K uptake was lower than during 2010 (Table 12), but K concentration in grains and straw indicate that plants were still sufficiently supplied with the nutrient after all treatments (results are not shown, Bergmann 1993; El-Nashaar et al. 2010).

160 kg N ha^{-1} minNPK resulted in the highest K uptake in grain and straw among all treatments and plants removed 24.5 kg K ha^{-1} more than applied with the fertiliser. Also at fertiliser rate 80 kg N ha^{-1} minNPK resulted in the highest K uptake in grain and straw compared with treatments of the same fertiliser rate, and plants removed 16.6 kg K ha^{-1} more than applied with the fertiliser, but uptake was not significantly different from fertilisation with minN+BWA, Hamar, CCW+BWA, CFS+BWA and Eko 6383 at the same fertiliser rate. However, also Mosvik, Hamar, CCW and CFS without BWA took up more K in aboveground biomass than applied with the treatment.

There was a significant effect of BWA on K uptake in grain and straw comparing minN treatments with and without BWA at both fertiliser rates. MinN treatments without BWA resulted in equally low K uptake in grain as the unfertilised control treatment, whereas minN in combination with BWA resulted in equally high K uptake in grain as minNPK at fertiliser level 80 kg N ha^{-1} and as all organic fertiliser treatments at fertiliser rate 160 kg N ha^{-1}. Moreover, application of BWA significantly increased K uptake in grain and straw in combination with 160 kg N ha^{-1} Hamar and 160 kg N ha^{-1} CFS.

All in all, the amount of plant-available K in the soil measured as K-AL tended to decrease in the course of the experiment after all fertiliser treatments with the exception of 70 kg K ha^{-1} BWA, 160 kg N ha^{-1} Hamar+BWA and 160 kg N ha^{-1} CCW+BWA, but there were no significant differences to K-AL values in the unfertilised control soil for any treatment (Table 13). BWA tended to result in higher K-AL values compared to respective treatments without BWA, but effects were not significant for any treatment. K-AL increase of 3 kg K-AL ha^{-1} in unfertilised control pots indicates potential artefacts during measurement and extrapolation. All fertiliser treatments resulted in negative total K balances (Table 11). Only BWA of both fertiliser rates and the highest rates of Eko 6353 supplied surplus K to both barley and wheat. K uptake exceeding K applied with fertiliser and plant-available K measured as K-AL indicates release of reserve-K for most of the treatments. The highest K supply from reserve-K was found after fertilisation with 80 kg N ha^{-1} minN, which resulted in total K uptake in plant biomass of 106 kg K ha^{-1} from reserve-K.

Table 11. K balances, effect of fertiliser treatments on readily available K (K-AL) as kg K ha^{-1} after wheat harvest and supply of K from reserve-K

	80 kg N ha^{-1}				160 kg N ha^{-1}			
	Total balances		K-AL change	Reserve-K supply	Total balances		K-AL change	Reserve-K supply
	Barley	Wheat			Barley	Wheat		
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Control	-30	-39	3	29				
BWA	1	25	-23		45	100	13	
minNPK	-83	-105	-81	17	-105	-119	-88	37
minN	-156	-214	-56	106	-129	-186	-85	42
minN + BWA	-123	-171	-52	72	-95	-126	-53	27
Mosvik	-87	-119	-67	35	-126	-183	-71	96
Mosvik + BWA	-48	-43	-29	7	-38	-33	-21	
Hamar	-89	-124	-88	36	-119	-155	-95	62
Hamar + BWA	-101	-104	-21	67	-96	-99	11	98
CCW	-58	-70	-66		-83	-110	-46	62
CCW + BWA	-48	-38	-41		-41	-19	81	91
CFS	-86	-119	-56	56	-99	-141	-87	54
CFS + BWA	-65	-73	-65	2	-55	-51	-27	20
Eko 8353	-78	-76	-46	16	-52	-37	-51	
Eko 6383	-29	-20	-55		4	40	-27	

Table 12. Effect of fertiliser treatments on P and K uptake in grain and straw of barley and wheat as kg ha^{-1}

	Barley 2010								Wheat 2011							
	80 kg N ha^{-1}				160 kg N ha^{-1}				80 kg N ha^{-1}				160 kg N ha^{-1}			
	P		K		P		K		P		K		P		K	
	grain	straw	grain	straw	grain	straw	grain	straw	grain	straw	grain	straw	grain	straw	grain	straw
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Control	0.8	0.9	1.1	20.9					0.6	0.1	0.8	3.5				
BWA	0.6	0.5	0.8	29.3	1.0	1.1	1.4	21.1	1.3	0.1	1.4	4.8	1.4	0.2	1.7	7.4
minNPK	6.8	1.3	13.8	104.4	9.0	2.7	25.7	148.3	5.7	0.2	12.2	40.4	9.7	0.5	24.5	72.7
minN	3.2	1.0	7.9	141.8	3.5	1.7	10.5	104.5	0.3	0.2	0.6	12.1	0.2	0.2	0.4	11.4
minN+BWA	5.4	1.4	10.0	142.6	6.1	1.8	14.0	136.0	3.2	0.2	7.1	34.2	4.7	0.2	12.3	57.4
Mosvik	7.0	1.0	12.1	75.1	8.7	1.9	18.8	108.4	2.1	0.1	4.2	14.8	5.8	0.5	11.9	37.9
Mosvik+BWA	7.6	0.8	11.8	70.4	11.8	1.6	20.7	90.8	4.4	0.2	8.4	18.9	6.7	0.3	12.8	43.2
Hamar	7.9	0.6	12.0	80.2	11.9	1.1	19.6	107.3	5.0	0.4	9.1	29.8	8.1	0.4	15.1	32.4
Hamar+BWA	6.9	1.0	10.7	127.1	8.8	1.0	13.1	157.8	3.7	0.3	6.6	21.3	7.8	0.3	14.4	59.1
CCW	5.2	0.8	9.3	58.2	9.3	1.1	16.3	87.5	3.9	0.2	7.0	15.4	6.3	0.2	13.3	41.3
CCW+BWA	5.3	0.8	8.7	84.8	9.0	1.4	13.8	115.9	4.8	0.2	8.5	29.6	9.4	0.4	15.3	55.4
CFS	8.1	1.1	11.1	71.7	10.4	1.6	15.7	85.3	6.1	0.2	10.2	21.5	8.7	0.4	15.1	31.0
CFS+BWA	7.2	1.1	10.6	89.4	10.7	1.6	16.1	109.3	5.2	0.3	8.7	30.2	9.8	0.4	15.8	51.1
Eko 8353	6.4	0.7	11.1	102.1	7.5	1.8	16.6	110.3	2.9	0.1	6.2	20.2	5.5	0.2	11.5	36.2
Eko 6383	4.8	1.4	9.0	66.2	6.6	4.2	18.0	73.1	3.2	0.1	7.6	28.3	5.0	0.2	11.6	40.2
MSE	4.2		8.3		4.2		8.3		2.1		4.2		2.1		4.2	

4.5 Soil pH, soil Ca-AL contents and Ca concentration in biomass

Liming of the experimental soil resulted in pH increase from 6.6 in Elverum sand to 7.2 as indicated by the unfertilised control (Table 13). The experimental soil was therefore slightly alkaline, and soil pH higher than originally intended. The amount of plant-available Ca, measured as Ca-AL, increased from 16 mg 100 cm^{-3} in the experimental soil to 28 mg 100 cm^{-3} in the control treatment, an amount that still was low according to Norwegian fertiliser recommendations (Landbrukets analysesenter n.d.), despite high soil pH.

Increasing amounts of BWA tended to result in increased soil pH, but there were only significant effects on soil pH after fertilisation of Hamar+BWA, when compared to fertilisation with Hamar at both fertiliser rates.

Overall, Ca concentration in plant biomass was very low, especially during the second year of the experiment (results are not shown, Bergmann 1993). Missing effect of BWA on Ca concentration in plant biomass let us, however, assume that Ca supply was no growth-limiting factor.

Table 13. Effect of fertiliser treatments on chemical soil properties

	80 kg N ha^{-1}				160 kg N ha^{-1}			
	pH	P-AL	K-AL	Ca-AL	pH	P-AL	K-AL	Ca-AL
Treatment		mg cm^{-3}	mg cm^{-3}	mg cm^{-3}		mg cm^{-3}	mg cm^{-3}	mg cm^{-3}
Control	7.2	2.1	6.0	28.4				
BWA	7.5	2.3	4.7	37.3	7.5	2.4	6.5	41.6
minNPK	6.9	1.9	1.8	34.7	6.8	2.1	1.4	31.2
minN	7.4	1.8	3.0	37.3	7.2	2.0	1.6	37.3
minN + BWA	7.6	2.0	3.2	42.5	7.8	2.1	3.2	50.3
Mosvik	7.1	2.8	2.5	30.3	7.1	4.3	2.3	42.5
Mosvik + BWA	7.4	4.6	4.4	50.3	7.6	12.1	4.8	61.5
Hamar	7.0	5.0	1.5	35.5	7.0	5.4	1.1	38.1
Hamar + BWA	7.6	5.5	4.8	41.6	7.7	9.9	6.4	63.3
CCW	7.0	1.7	2.5	27.7	7.1	1.8	3.5	35.5
CCW + BWA	7.4	2.7	3.8	38.1	7.7	2.4	9.9	41.6
CFS	7.2	2.8	3.0	35.5	7.0	4.2	1.5	37.3
CFS + BWA	7.3	3.8	2.6	45.1	7.5	5.5	4.5	48.5
Eko 8353	7.1	3.3	3.5	35.4	7.1	6.3	3.3	42.5
Eko 6383	7.0	4.3	3.1	33.8	7.0	6.2	4.5	43.3
MSE	0.6	7.7	6.1	26.1	0.6	7.7	6.1	26.1

5. Discussion

5.1 N use efficiency and mineral fertiliser equivalents of organic waste resources

The present experiment indicated that N-rich waste resources can, under field conditions, potentially result in equally high N uptake in grain as mineral compound fertilisers. Equally high N uptake after fertilisation with organic waste resources and minNPK during 2010 can to a large extend be explained by organic waste resources being less prone to leaching than mineral fertilisers. Similar results have earlier been described by Haraldsen et al. (2011a). During 2010, NUE (%) of organic waste resources were therefore very well in accordance with studies on N fertilisation effects of MBM and CCW that were based on field experiments or pot experiments including a leaching episode (37 % Salomonsson et al. 1994; 42-25 % Jeng et al. 2004; 30-41 % Chen et al. 2011; 31-35 % Haraldsen et al. 2011a). When we intentionally avoided N losses during 2011, minNPK treatments resulted in the highest NUE (%) among all treatments. Mineral N residues in soil after fertilisation with 160 kg N ha^{-1} minN during 2011 indicate, however, that immediately soluble mineral fertilisers would have come out less favourable in comparison to organic waste resources, if we had simulated another shower precipitation during the second year of the experiment.

Another reason for equally high NUE (%) of organic waste resources and minNPK during 2010 may be that barley plants were forced to ripen before ripening would normally have been physiologically intended, caused by the unintended drought period just after the leaching episode. Remaining mineral N in the soil could, hence, not be utilised by plants and therefore, potential differences in N fertilisation effects of organic waste resources and minNPK were levelled out. This is also underpinned by the fact that there were no significant differences between effects of increasing fertiliser rates during 2010 and that higher fertiliser rates resulted in lower NUE (%), whereas application of the doubled fertiliser rate resulted almost throughout in significantly higher NUE (%) during 2011.

During 2011, NUE (%) of organic waste resources were not only significantly lower than NUE % of minNPK, but also lower than during 2010 and lower than NUE (%) presented by Salomonsson et al. (1994), Jeng et al. (2004) and Chen et al. (2011). Reduced NUE (%) during 2011 compared with 2010 can partly be explained by a shorter growth period of wheat compared to barley. Whereas barley was harvested after 83-84 days, wheat was harvested after 71 days. Therefore, there were 12-13 more days for waste resources to mineralise during 2010. Moreover, during 2011 there was reduced temperature in the greenhouse. Transformation of organic N into NH_4 and nitrification to NO_3 has been found to be a function of temperature, with increasing mineralisation rate of N in swine slurry at increasing temperature (Griffin et al. 2002). The results of the present experiment emphasize therefore that fertilisation effects of organic waste resources are to a higher degree dependent on environmental conditions than mineral fertilisers.

During 2010 MFE (%) on N uptake were higher than MFE (%) on yield. During 2011 MFE (%) on yield were higher than MFE (%) on N uptake, as earlier presented by Brod (2011). This means that plants fertilised with organic waste resources might produce as much biomass while nutrient contents are lower. MFE (%) on both yield and N uptake tended to decrease for higher fertiliser rates. Only CCW showed an increasing tendency for fertiliser efficiency with increasing rates.

5.2 Synchronisation of N mineralisation with crops' demands in time

During both years of the experiment, minNPK and minN resulted in higher straw production than organic waste resources, indicating a head start of mineral fertilisers regarding initial availability of mineral N. Similar results have earlier been described by Haraldsen et al. (2011b). Availability of N during early plant development increases the survival rate of shoots, the amount of spikes and kernel numbers per spike and therewith the yield (Spiertz & De Vos 1983; Mossedaq & Smith 1994). High leave and straw biomass is moreover advantageous as grain filling is rather determined by translocation of N from the vegetative parts of the cereal plant to the kernels than by plant-available N in the soil (Spiertz & De Vos 1983; Heitholt et al. 1990). Therefore, a lack of mineral N at the beginning of the growing season after fertilisation with organic waste resources is to be looked at as drawback regarding their overall fertilisation effects. Reduced vegetative growth after application of organic waste resources resulted in MFE (%) on total yield being lower than MFE (%) on grain yield (Table 7, Table 8).

Overall, plants utilised only a small fraction of N applied with organic waste resources during both years, leaving considerable N residues in the soil at the end of the experiment, which continued to mineralise after wheat harvest, even though at a lower rate. Also Delin & Engström (2010) and Cordovil et al. (2012) found continuous mineral N release after application of organic waste, even though net mineralisation flattened clearly out, when recalcitrant N components predominated after initially fast mineralisation. N mineralisation throughout autumn can hardly be matched with the crops' demands, but has to be regulated by catch crops, if losses and associated environmental challenges should be avoided. Accordingly, equally high N uptake during 2011 as during 2010 after fertilisation with CCW can probably be traced back to slow release of residual N compounds. Also studies of Haraldsen et al. (2011b) indicate that mineralisation of N in CCW is good, but too slow to match with nutritional demands of cereals.

5.3 P fertilisation effects of bottom wood ash

Based on extraction of P in BWA with ammonium lactate + acetic acid (P-AL) we assumed that only 11% of BWA-P were plant-available. These assumptions are in accordance with studies of Ohno and Erich (1990), who suggested based on P extraction with ammonium acetate that around 6% of total P in wood ashes is directly available to plants. Also Erich (1991) proposed that extraction of P in ashes with ammonium acetate is better suited as indicator for available P in ashes than the total P content.

When soil P reserves were depleted during the second year of the present experiment, P in BWA compensated, however, for 73.3-91.1% of P in minNPK after combination with minN. Also Schiemenz et al. (2011) suggested that P fertilisation effects of ashes can be compared with highly soluble P fertilisers as superphosphate. Extraction of P with ammonium lactate + acetic acid (P-AL) seems therefore not to be suited to indicate the amount of plant-available P in ashes. In Norway, the P-AL method buffered at pH 3.75 is commonly used to measure the amount of plant-available P in slightly acidic soils. Probably oxides, hydroxides, carbonates of basic cations in BWA caused an increase of pH in the buffer solution that decreased the amount of easily soluble P and resulted in an underestimation of the amount of plant-available P in BWA. According to Schiemenz et al. (2011) 80% of P in ashes is extractable in citric acid, which might therefore be better suited to predict P fertilisation effects of BWA. To be able to predict the P fertilisation effect of wood ashes, further studies on reliability of analytical methods and their synchronisation with crop responses are needed.

The P fertilisation effect of BWA was only evident after application in combination with minN that provided sufficient amounts of directly plant-available N. After application of BWA alone, plants were deficient in N, and P in BWA could therefore not be utilised.

5.4 P fertilisation effects of MBM and Global Enviro composts

Deficient P supply after fertilisation with 80 kg N ha^{-1} Mosvik, Eko 8353 and Eko 6383 during 2011 can probably be traced back to alkaline soil conditions. According to Jeng et al. (2006) P in MBM is present as organic P in the meat fraction, which can easily be taken up by the plants, and as apatite ($Ca_5(PO_4)_3OH$) in the bone fraction, requiring dissolution by H^+ to become available to plants. Bøen (2010) suggested that around 93% of MBM-P is bound as Ca phosphates in the bone fraction. After the present experiment, soil pH was > 7 after fertilisation with 80 kg N ha^{-1} Mosvik, Eko 8353 and Eko 6383 as result of the unintended strong liming effect of 0.53 g $CaCO_3$ L^{-1} soil. Hence, bone-P could probably not be utilised by the plants. It seems therefore as if extraction of MBM-P with ammonium lactate + acetic acid (P-AL) overestimates the amount of plant-available P under alkaline soil conditions, and that its suitability as indicator for the P fertilisation effect of MBM is strongly dependent on soil pH. Likewise Ylivainio et al. (2008) proposed that extraction of MBM-P with acid ammonium acetate at pH 4.65 is not in agreement with the amount of P plants can utilise, after conducting a pot experiment with ryegrass as experimental crop and limed loamy sand with pH 6.5 as experimental soil.

CCW and CFS resulted in equally high or higher P uptake than MBM, even though less P was applied with the Global Enviro composts. This indicates that P fertilisation effects of CCW and CFW are independent of soil pH.

In order to predict P fertilisation effects of the P-rich waste resources MBM, CCW and CFS, further studies on reliability of analytical methods and their synchronisation with crop responses are needed.

5.5 K fertilisation effects of BWA

The soil managed to supply plants with much more K than expected based on analyses of plant-available K measured as K-AL previous to the experiment. High soil-K release in agreement with findings of Øgaard et al. (2002), who studied the ability of Norwegian soils to supply grass with K and who found that even sandy soils can contribute with considerable amounts of plant-available K originating in reserve-K in addition to exchangeable K (K-AL). During the first year of the experiment, potential K fertilisation effects of BWA were therefore hidden by the soil's ability to provide plant-available K.

During 2011, minN and the highest fertiliser rates of minN+BWA, Hamar, CCW and CFM resulted in K:N ratios in plant biomass being somewhat lower than 0.8 (results are not shown), indicating limited K supply after fertiliser treatments with high N supply (Øgaard & Hansen 2010). Therefore yield increase after combination of minN with BWA can possibly be attributed to combined P and K fertilisation effects of BWA. Also significantly increased K uptake in aboveground biomass after combination of 160 kg N ha^{-1} Hamar and CFM with BWA indicates potential K fertilisation effects of BWA. Likewise, Øgaard and Hansen (2010) found that K fertilisation can become visible as increased K concentration in plant biomass despite lacking yield response of herbage.

To prove K fertilisation effects and to calculate K utilisation efficiencies of BWA a long-term experiment with K-sufficient experimental soil and controlled supply of N and P will have to be conducted.

Effects of BWA on soil pH were not significant. Therefore, it seems as if BWA used in the present experiment is better suited as ingredient in alternative NPK fertiliser products than BWA tested by previous studies of Haraldsen et al. (2011a).

6. Conclusion

During the first year of the experiment, when shower precipitation was simulated and when drought forced cereals to ripen earlier than physiologically intended, organic waste resources resulted in relative N utilisation of 60-120% in grain compared with mineral compound fertiliser and mineral fertiliser equivalents on grain yield were between 50-90%. Under controlled conditions during the second year of the experiment, organic waste resources resulted in relative N utilisation of 30-60% in grain compared with mineral compound fertiliser, and mineral fertiliser equivalents on grain yield were between 30-80%.

The experiment indicated that P in BWA can have almost the same availability as easily soluble P in mineral fertilisers and that plant availability of P in MBM is strongly determined by soil pH. To be able to predict the P fertilisation effect of P-rich waste resources, further studies on the reliability of analytical methods and their synchronisation with crop responses are needed.

Potential K fertilisation effects of BWA were hidden by the soil's ability to provide plant-available K during the first year, but increased K uptake in aboveground biomass at sufficient N supply and increased amounts of plant-available K in the soil during the second year of the experiment indicate that the K fertilisation value of BWA might be detected by a long term experimental approach with controlled supply of N and P.

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