Combined Waste Resources as NPK Fertiliser: Results from a Pot Experiment

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PREFACE

As all students of the master programme Agroecology at the Norwegian University of Life Sciences in Ås, I was asked to write my master thesis in the form of a scientific paper. Therefore, this thesis is an article aiming at publication in the Elsevier journal Agriculture, Ecosystems & Environment. Appendices contain literature review and research that I needed in order to gain a rich picture of the topic but that would have exceeded the boundaries of a scientific paper.

The experiment, which this paper is based on, was carried out as part of CenBio, Bioenergy Innovation Centre (http://www.cenbio.no), which is supported by the Research Council of Norway, Norsk Protein AS and Akershus Energi AS. Moreover, the project was financially supported by Dynea ASA.

I want to thank Trond Knapp Haraldsen for taking the position of the main thesis advisor, for planning of the experiment, for his time, enthusiasm, patience and guidance through my work. Professor Tor Arvid Breland is thanked for his support with regards to the holistic view of an agroecological thesis. Hege Bergheim is thanked for skilful technical assistance and experimental work. Also I want to thank professor Tore Krogstad for providing laboratory localities and enabling timely analyses of all of the samples. Irene Eriksen Dahl, Valentina Zivanovic, Solfrid Lohne and Kurt Johansen are thanked for help with laboratory analyses. Anita Nipen, Maren Holthe and Anne Bøen are thanked for language correction, critical questions and discussion of the results. This thesis would not have been what it is without these people.

ABSTRACT

Returning waste to agricultural land is a holistic systems approach to meet the challenging task of future food supply. As nutrient contents in organic material often are unbalanced in comparison to the plants' needs, the aim of this paper was to study the fertilisation effect of waste-based NPK compound fertiliser products and their potential to substitute conventional fertilisers in agricultural plant production.

A pot experiment with Italian ryegrass (*Lolium multiflorum* var. *italicum*) as experimental crop was conducted where the four N-rich waste resources meat and bone meal (MBM), composted fish sludge (CFS) and two types of industrial compost (Dynea 2009 and Dynea 2004) were tested alone and in combination with K-rich bottom wood ash (BWA). Fertilisation levels (150 kg N ha^{-1} + 120 kg K ha^{-1}; 300 kg N ha^{-1} + 240 kg K ha^{-1}) were based on total N and K content in N-rich waste and BWA, respectively. Treatments with BWA, artificial compound fertiliser (minNPK) and calcium nitrate (minN) only, as well as an unfertilised control were used as references.

Availability of mineral N was the key limiting factor to plant growth. Mineral fertiliser treatments resulted in the highest total yields being significantly different from all waste combinations. Plants that received MBM or CFS fertilisation had good and even biomass production throughout the season, but fertilisation effects were limited by mineralised N. Mineral fertiliser equivalents of MBM and CFS treatments were between 48-73%. MBM treatments increased the amount of soluble P in plant-soil systems to amounts that were higher than total P applied with the fertiliser product. MBM might therefore be a more valuable alternative P-fertiliser than one assumed so far. CFS seems to be more appropriate as an ingredient in alternative NPK fertiliser products than MBM because of reduced effects on residual P in the soil, good availability of P in the material, as well as a wider N:P ratio and relatively high initial amounts of mineral N. Dynea composts had poor fertilisation effects and can therefore rather be classified as soil conditioners than as fertilisers. K fertilisation effect of BWA was hidden by sufficient K supply from the soil but K-AL values of soils that were fertilised with BWA were significantly higher than soils of unfertilised control treatments. MinN + BWA treatments had poor establishment due to local pH increase and initial P deficiency, but leaching or denitrification of NO_3-N was avoided so that the treatments still resulted in vigorous plant growth towards the end of the season.

Before waste-based NPK fertiliser products are ready for commercial production, further studies have to be done on the optimisation of their N fertilisation value.

Keywords: Waste resources, nitrogen, phosphorus, fertiliser, meat and bone meal, composted fish sludge, bottom wood ash.

TABLE OF CONTENT

ILLUSTRATIONS

ABBREVIATIONS

Al	Aluminium
AL	Aluminium lactate
BWA	Bottom wood ash
Ca	Calcium
Ca-AL	Readily available Ca, determined after extraction with acetic acid and ammonium lactate
CCE	Calcium carbonate equivalent
Cd	Cadmium
cm	Centimetre
Cr	Chrome
Cu	Cobber
CFS	Composted fish sludge
C:N	Ratio of carbon to nitrogen
CO_2	Carbon dioxide
DON	Dissolved organic nitrogen
DM	Dry matter
Dynea (2009)	Neutral Dynea compost (pH 7.3)
Dynea (2004)	Acid Dynea compost (pH 3.5)
Fe	Iron
g	Gram
h	Hour
ha	Hectare
HCl	Hydrochloric acid
Hg	Mercury
HNO_3	Nitric acid
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
K	Potassium
K-AL	Readily available K, determined after extraction with acetic acid and ammonium lactate
KCl	Potassium chloride
kg	Kilogram
l	Litre
LCA	Life cycle analysis
M	Mole
MBM	Meat and bone meal
MFE	Mineral fertiliser equivalent
mg	Milligram
Mg	Magnesium
Mg-AL	Readily available Mg, determined after extraction with acetic acid and ammonium lactate
minN	Calcium nitrate
minNPK	Yara Fullgjødsel® 18-3-15
mm	Millimetre
Mn	Manganese
MSD	Minimum significant difference
N	Nitrogen
Na	Sodium
N:P	Ratio of nitrogen to phosphorus
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
N_{min}	Mineralised nitrogen
N_2O	Nitrous oxide
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NO_x	Generic term for NO and NO_2
NPK	Compound fertiliser with the components nitrogen, phosphorus and potassium
P	Phosphorus
P-AL	Readily available P, determined after extraction with acetic acid and ammonium lactate
PO_4^{3-}	Phosphate

Pb	Lead
pH	Measurement of the molar concentration of dissolved hydrogen ions
S	Sulphur
TOC	Total organic carbon
v	Volume
w	Weight
Zn	Zinc

GLOSSARY

Agroecosystem	An ecosystem that is modified to produce commodities for human use and that hence is influenced by environmental, economic and social impacts (Gliessman, 2007).
Biogeochemical cycle	'The manner in which the atoms of an element critical to life (...) move from the bodies of living organisms to the physical environment and back again.' (Gliessman, 2004)
Ecosystem	'…a functional system of complementary relations between living organisms and their environment, delimited by arbitrarily chosen boundaries, which in space and time appears to maintain a steady yet dynamic equilibrium.' (Gliessman, 2004)
Emergy analysis	Energy analysis of a service or product where direct and indirect energy inputs of all kind are transformed into the same unit (Rydberg and Haden, 2006).
Eutrophication	'Degradation of water quality owing to enrichment by nutrients, primarily nitrogen (N) and phosphorus (P) which results in excessive plant (principally algae) growth and decay.' (Smil, 2011)
Green Revolution	Industrialisation of agriculture and increase of yields in the middle of the 20th century due to advances in breeding and the introduction of artificial fertiliser and chemical plant protection.
Life cycle analysis	Method to assess impacts of a service or product on the environment taking into account all associated up- and downstreams from production to transport, consumption and disposal.
Mineralisation	Transformation of nutrients in organic material into forms, which can be taken up by plants.
Mineral fertiliser equivalents	Mineral fertiliser equivalents represent the amount of N that has the same availability to plants as N applied with mineral fertiliser, calculated based on N taken up by the crop and presented as rate of total N applied (Delin *et al.* 2011).
Organic fertiliser	Material, which exclusively originates from animal or plant sources and which has a loss of ignition of at least 40% of dry matter (Norwegian Ministry of Agriculture 2003, appendix 1).
Peak oil	Point of time from when global oil extraction rate will decline.
Sanitation	Treatment of organic fertiliser material to avoid infection of contagious diseases to humans, animals and plants (Norwegian Ministry of Agriculture, 2003, §10).
Stabilisation	Treatment of organic fertiliser material to reduce undesirable odours and potential pollution of the environment (Norwegian Ministry of Agriculture, 2003, §10).
Sustainability	Ability to maintain natural processes and functions in the future.
Waste	Undesirable or unusable material.

1 INTRODUCTION

Terrestrial ecosystems are characterised by local biogeochemical cycles: Nutrients are recycled when they move from decomposed biotic material to the soil system before they are again taken up by plants (Chapin *et al.*, 2002). Despite constant internal dynamism, in the long run ecosystems seem to be stable with regards to their overall nutrient movement and are therefore considered to be sustainable (Gliessman, 2004, 2007) if sustainability is defined as the ability to maintain natural processes and functions in the future.

In agroecosystems, humans make use of natural ecosystems for the production of commodities for their own use (Gliessman, 2007). Whereas ecosystems are self-sustaining, agroecosystems are highly dependent on human impacts. When nutrients are removed from agroecosystems with the harvest or as a result of leaching or erosion, they are commonly replenished through the external input of fertilisers.

Traditional agroecosystems return nutrients to agricultural land by fertilisation with organic waste residues or animal manure and cropping of legumes (Smil, 2011). In many agroecosystems all over the world, ash resulting from slash and burn activities is a common way to supply crops with essential nutrients (Gliessman, 2007). Traditional Norwegian agroecosystems use the forest as a source of plant nutrients when livestock are rough grazing the woods and their dung is applied to agricultural fields nearby the farm.

In industrialised agroecosystems artificially produced fertilisers have been popular since the Green Revolution, as they provide farmers controlled application of nutrients. Today it is commonly known that there are various negative impacts on the environment connected to the use of synthetic fertilisers, including accumulation of biologically reactive N in the atmosphere, acidification of soils, eutrophication of fresh water as well as marine coastal areas and depletion of fossil fuel and phosphate rock (Chapin *et al.*, 2002; Cordell *et al.*, 2009; Smil, 2011)[1]. At the same time, a high fraction of valuable nutrients that are introduced to today's agroecosystems with readily soluble fertilisers, end up in unused waste residues. Overall, large-scale agriculture strongly influences natural biogeochemical processes resulting in nutrient cycles commonly being disrupted and replaced by linear nutrient flows (Chapin *et al.*, 2002).

[1] See Appendix I: Background: Challenges connected to the use of artificial N and P fertiliser.

In the future, the world-wide demand for biomass production will most likely continue to grow mainly due to global population growth, cropping of first generation biofuels and the human preference for animal protein based diets even in traditionally vegetarian cultures (Cordell *et al.*, 2009; Dawson and Hilton, 2011). Hence also the demand for artificial fertilisers will increase as well as the associated environmental impacts. It seems as if continuing today’s agricultural practice will lead us to a dead end street. Therefore, a change of thinking is crucial to ensure plant nutrition and hence global human nutrition in the future.

According to Gliessman (2004) agroecosystems can only be sustainable if natural ecosystem principles are applied to the management of agricultural activities and if the input of artificially produced fertilisers is kept to a minimum. In resource efficient agroecosystems, natural nutrient cycles are used as a model, and linear nutrient flows are replaced by recycling of nutrients that were originally taken up by agricultural products (Gliessman, 2004; Pyper, 2006). When waste is looked upon as material, which ‘has not exhausted its being’ yet (Lie, 2009), it turns from an undesirable rest product into a resource. Re-circulating waste is a holistic systems approach to some of the main challenges of today’s agriculture. Therefore, the development of waste-based compound fertiliser products is a step forward in re-closing natural nutrient cycles.

There are many derivatives from the food industry as well as waste products from industry and bioenergy plants that are considered as waste problems despite considerable contents of valuable plant nutrients. It seems as if there is an unexploited potential for the use of these by-products as fertilisers in agriculture (Haraldsen *et al.*, 2011).

Still, there are several aspects that keep many farmers from applying them to agricultural land. Some of the major challenges associated with the re-use of waste in agriculture are minimum requirements according material quality (Norwegian Ministry of Agriculture, 2003, §10), energy- and cost intensive transport of products with low dry matter contents, as well as even application of bulky or dusty waste. The main issue with regards to the use of waste resources as fertiliser, however, seems to be a lack of knowledge about their actual fertilisation and liming effects, and that NPK ratios in waste material usually are unbalanced in comparison to the plants’ needs (Haraldsen and Krogstad, 2011; Haraldsen *et al.*, 2011)[2]. Therefore, detailed information about each single waste resource has to be gained regarding nutrient content, decomposition and min-

[2] See Appendix I: Background: Challenges connected to the use of waste as fertiliser

eralisation dynamics to turn waste into a valuable resource[3]. Combining various waste resources could be a possibility to overcome the challenge of unbalanced NPK ratios in waste material.

Haraldsen *et al.* (2011) tested the concept of recycled NPK fertiliser of organic origin by combining meat and bone meal (MBM) with bottom wood ash (BWA) in an experiment where the waste resources were applied to spring cereals. In spring barley (*Hordeum vulgare*) the combination of MBM and BWA gave a yield as high as mineral fertiliser, which was significantly higher than the yield of plants that were fertilised with MBM alone (Haraldsen *et al.*, 2011).

Haraldsen and Krogstad (2011) combined the N-rich waste resources MBM, composted source separated catering and household waste and composted sediments from fish farming with BWA in a two year pot experiment with barley (*Hordeum vulgare*) as first year and wheat (*Triticum aestivum*) as second year experimental crop. The results indicated that BWA has potential P and K fertilisation effects. During the first year of the experiment, N-rich waste resources had more efficient N fertilisation effects than calcium nitrate treatments as a result of a leaching episode during early plant development (Haraldsen and Krogstad, 2011).

Kuba *et al.* (2008) studied the effect of a combination of compost with wood ashes and found that the addition of wood ashes improved the compost quality. When compost mixed with ashes was added to the soil, microbial activity in the soil measured as respiration was enhanced indicating improved degradability of the compost material (Kuba *et al.*, 2008).

Pradhan *et al.* (2010) researched the combination of human urine and wood ash in a field experiment on red beet (*Beta vulgaris*). Total biomass production of plants fertilised with the waste-based fertiliser combination was somewhat higher than biomass production of crops that received mineral fertiliser amendments, even though differences were not significant. The combination of waste resources resulted furthermore in greater root production than mineral fertiliser amendments (Pradhan *et al.*, 2010).

Several studies have already dealt with the forward-looking concept of alternative NPK fertilisers based on waste residues. However, more research has to be done on specific mixtures of various waste resources to gain knowledge about possibilities to develop alternative, balanced NPK fertilisers of organic origin for commercial production, with the potential to substitute artificial

[3] See Appendix I: Background: Decomposition of organic matter and nutrient mineralisation dynamics.

compound fertiliser, and to re-close natural nutrient cycles. Consequently, the aim of this paper was to provide answers to the following questions:

How can various waste resources be combined to develop sustainable NPK fertiliser products with the potential to substitute conventional compound fertilisers?

How fast is N in various waste resources mineralised and available to crops?

How is the P and K fertilisation value of various waste resources to be assessed?

These questions were investigated by a pot experiment where Italian ryegrass (*Lolium multiflorum* var. *italicum*) was fertilised with various waste resources: Mixtures of different N-rich waste and K-rich bottom wood ash were compared with the fertilisation effects of compound mineral NPK fertiliser (minNPK, Yara fullgjødsel® NPK 18-3-15), calcium nitrate (minN), bottom wood ash (BWA) and an unfertilised control.

N mineralisation rate of N-rich organic waste resources was determined indirectly by N uptake of Italian ryegrass as response to fertiliser application. Aboveground biomass was a method to observe N-dynamic and the temporal dimension of mineralisation. Also P and K fertilisation effects were measured as uptake in aboveground biomass.

2 MATERIALS AND METHODS

2.1 Waste resources

In the experiment five Norwegian waste resources that all originated from industrialised food production or other industry activities were tested. Meat and bone meal (MBM), composted fish sludge (CFS) and neutral and acid Dynea compost (Dynea 2009, Dynea 2004) are N-rich materials. MBM and CFS also contain considerable amounts of P. Bottom wood ash (BWA) is considered a valuable source of K. Even though BWA also contains some P, the fraction of plant available P in the specific BWA used was low according to chemical analysis of the waste resource. Table 1 is a brief description of waste resources used in the experiment.

Table 1: Description of waste resources[4].

Waste resource	Short name	Nutrient	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 consists of 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.
Meat and bone meal	MBM	N and P	Stabilised, sanitised 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 is a mixture of feed residues and excrements (sediments) from a flow-through hatchery of the company Åsen settefisk AS (63°61'N, 11°05'E) in Trøndelag, Norway. The sludge is composted by reactor physiology of the company Global Enviro International AS.
Neutral Dynea compost	Dynea 2009	N	Industrial compost. Parent material is based on N-rich effluent from chemical industry activities of the international company Dynea ASA, which is located in Lillestrøm (59°96'N, 11°05'E), Norway. The effluent is cleaned through a microbial filter. N-rich microbial biomass of the filter is mixed with wood chips before the material is composted in windrows outside.
Acid Dynea compost	Dynea 2004	N	Industrial compost with the same parent material as Dynea 2009. An acidification process happened during storage of the waste resource: Polymers of formaldehyde broke down to formic acid that gradually lowered the pH in the material to around 3.5.

[4] See Appendix II: Waste resources for detailed description of the waste resources.

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 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 content was determined by the modified Kjeldahl method (EN 13654-1, 2001). NO_3-N and NH_4-N were determined after extraction with 2 M KCl (Henriksen and Selmer-Ohlsen, 1970; Selmer-Ohlsen, 1971).

To determine the content of total organic carbon, 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 (P-AL), K (K-AL), Mg (Mg-AL) and Ca (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 summarises the chemical properties of each of the waste resources that were applied as fertiliser in the experiment.

Table 2: Chemical properties of bottom wood ash (BWA), meat and bone meal (MBM), composted fish sludge (CFS) and neutral (Dynea 2009) and acid (Dynea 2004) Dynea compost.

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
TOC, g $(100g)^{-1}$ DM	0.1	41.3	51.2	38.4	36.6
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_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		0.15		
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

See Abbreviations for an explanation of the abbreviations.

Table 3: Content of heavy metals in bottom wood ash (BWA), meat and bone meal (MBM), composted fish sludge (CFS) and neutral (Dynea 2009) and acid (Dynea 2004) Dynea compost.

Parameter, unit	BWA	MBM	CFS	Dynea 2009	Dynea 2004
Cd, mg kg^{-1} DM	0.60	0.02	0.40	0.21	0.27
Cr, mg kg^{-1} DM	15.00	1.60	1.70	15.00	16.00
Cu, mg kg^{-1} DM	75.00	8.70	11.00	42.00	59.00
Hg, mg kg^{-1} DM	0.00	0.01	0.01	0.18	0.73
Ni, mg kg^{-1} DM	16.00	1.80	0.53	32.00	22.00
Pb, mg kg^{-1} DM	7.80	1.10	0.35	33.00	31.00
Zn, mg kg^{-1} DM	200.00	99.00	290.00	150.00	84.00

See Abbreviations for an explanation of the abbreviations.

All of the resources used in the experiment could be applied to agricultural land as fertiliser in Norway (for content of heavy metals in the waste resources see Table 3).

MBM was in quality class 0 considering the content of heavy metals in the material. Therefore, there are no restrictions regarding the amount of MBM that could be applied on agricultural land despite the plants' demand. BWA and CFS were in quality class I, their use on agricultural land would therefore be restricted to 40 t dry matter of the material per ha in 10 years. Both Dynea 2009 and Dynea 2004 were in quality class II, therefore the use on agricultural land would be restricted to 20 t dry matter of the material per ha in 10 years (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 (Blytt *et al.*, 2011). The content of heavy metals in CFS was at the same level of Norwegian animal manure of different types of animals (Paulsrud *et al.*, 1997). The use of CFS in organic farming seems therefore to be in accordance with the Norwegian legislation (Mattilsynet, 2009).

2.2 Soil

The soil used in the experiment originated from a former organic experimental plot in Kise (60°78'N, 10°81'E) in the municipality Ringsaker in Norway. Rocks in this area are calciferous dolomite rocks. Sediments are typically morainic soils (NGU, 2011). The soil used is a sandy loam containing high fractions of gravel and organic matter. The particle size distribution of the soils was determined according to Elonen (1971). Table 4 is an overview over distribution of the size of soil particles.

Table 4: Size of soil particles of experimental soil.

	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: 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

See Abbreviations for an explanation of the abbreviations.

Table 5 describes the chemical characteristics of the soil used in the experiment. 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 M HNO_3 solution (Pratt, 1965). pH was determined in a soil water suspension of 1:2.5 (v/v).

The soil was slightly acidic. Contents of readily available P (P-AL) were low, contents of readily available K (K-AL) were intermediate. All in all K-reserves measured as acid-soluble K (K-HNO_3) were low (Bioforsk, 2003). The low nutrient values in the soil were supposed to enable the evaluation of NPK fertilisation effects of the waste resources. Due to the soil's origin in calciferous dolomite rocks, there were considerable amounts of Mg-AL and high amounts of Ca-AL in the soil (Landbrukets analysesenter, s.a.). The waste resources were not assessed according to 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.

In 2009 the same soil was used for an experiment with Chinese cabbage where different liming strategies were tested. The year after, wheat was grown on the soil to test the fertilisation value of digestate from biogas plants. In both cases, fertilisation 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 used in the experiment had been stored under adequate conditions for the last three years. For the experiment, all of the soil was thoroughly mixed and possible influences of previous activities were therefore evenly distributed on all experimental treatments.

After the soil had been mixed, it was sieved at a mesh width of 4 mm before it was filled into the 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_3-N and NH_4-N were determined as described.

2.3 Experimental design

The experiment was conducted outside under a large glass roof at the experimental station of the Soil and Environment Department of the Norwegian Institute for Agricultural and Environmental Research in Ås, Norway (59°39'N, 10°45'E). Kick/Brauckmann pots (7.5 l with a top diameter of 21.5 cm) were located randomized side by side on a table so that the plants were protected from precipitation but otherwise exposed to daylight and outdoor climate. Temperature data for the growing season is given in Table 6. The season was slightly warmer than average summers in the area. The plants were irrigated three times a week. Each pot was watered up to a water level of 0.35 m^3 m^{-3} equivalent to field capacity of the soil.

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 experimental crop was Italian ryegrass (*Lolium multiflorum* var. *italicum* cv. Macho). Italian ryegrass is found naturally on rich soils where sufficient nutrients are available, and hence biomass commonly clearly increases in response to fertilisation (Frame, 1992). The characteristics of Italian ryegrass make it a good indicator for the amount of plant available nutrients in the soil. The crop was therefore used as a tool to study mineralisation rates and fertilising effects of the various waste resources indirectly by the uptake of nutrients in the 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 per pot.

Planting took place on Monday, 9 May 2011. The upper 5 cm of soil in the pots were removed and fertiliser was applied equally on the soil together with the seeds. Then the upper soil layer was placed back on top. Applications of seeds and fertilisers at the same depths imitate the mechanism of combine drills, but seeds were hence placed deeper than commonly recommended for grasses. 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 fertilisation throughout the summer.

The experiment was designed to supply the plants with NPK similar to that supplied by the use of the compound fertiliser Yara Fullgjødsel® 18-3-15. All of the four N-rich waste resources were tested alone and in combination with K-rich BWA. Additionally there were treatments with BWA, the artificial compound fertiliser Yara Fullgjødsel® 18-3-15 (minNPK), calcium nitrate (minN) alone and an unfertilised control as references. Each treatment 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 150 kg N ha^{-1} + 120 kg K ha^{-1} and 300 kg N ha^{-1} + 240 kg K ha^{-1}. All amounts of added fertiliser were calculated on hectare to pot basis. The low fertiliser levels were based on normal N fertilisation recommendations for pastures with three cuts in Norway (Bioforsk, 2003). The higher fertiliser levels were calculated by doubling the amount. There were three replicates for each of the treatments. For the experimental design see Table 7.

Table 7: Amount of waste resources applied with contents of mineral N, total P, P-AL and total K/K-AL (kg ha^{-1}).

Fertiliser	Amount applied (150 kg N ha^{-1} + 120 kg K ha^{-1})					Amount applied (300 kg N ha^{-1} + 240 kg K ha^{-1})				
Amount/ nutrient	Amount	N_{min}	Total P	P-AL	Total K/ K-AL [a]	Amount	N_{min}	Total P	P-AL	Total K/ K-AL [a]
Unit	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	0	0	0	0	0	0	0	0	0
BWA	1875	0	32	4	120	3750	0	64	7	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	2843	150	32	4	120	5685	300	64	7	240
MBM	1667	1	75	33	5	3333	1	150	67	9
MBM + BWA	3542	1	107	37	125	7083	1	214	74	249
CFS	2174	6	37	35	7	4348	11	74	70	13
CFS + BWA	4049	6	69	38	127	8098	11	138	77	253
Dynea 2009	2055	2	4	2	1	4110	4	8	4	3
Dynea 2009 + BWA	3930	2	36	5	121	7860	4	72	11	243
Dynea 2004	1923	5	6	1	0	3846	9	12	2	0
Dynea 2004 + BWA	3798	5	38	5	120	7596	9	76	10	240

[a] K in BWA is calculated based on total K in the material, K in other material is based on K-AL.
See Abbreviations for an explanation of the abbreviations.

The biomass was harvested four times throughout the season with an average time interval of one month between two harvests. Harvests were carried out on 21 June, 19 July, 17 August and 27 September 2011. The exact date was adapted to plant development each time. The biomass was harvested manually with scissors at a height of 1.5 cm from soil surface. For each harvest biomass production in each pot was measured. The plant material was dried at 40°C for one week, dry matter production was calculated and chemical analysis was conducted for one pooled sample per treatment. Total N in the plant material was determined by the Dumas method (NS-EN 13654-2, 2001). Total tissue concentration of P and K was determined by the same method as described above for the waste resources.

2.4 Nitrogen effects of fertiliser treatments

For all treatments mineral fertiliser equivalents were calculated. Mineral fertiliser equivalents represent the amount of N that has the same availability to plants as N applied with mineral fertiliser. To calculate mineral fertiliser equivalents the amount of N that mineralised from the soil organic matter in control treatments was subtracted from N uptake after each fertiliser treatment.

The total N amount applied with the fertiliser was set to 100% (Equation 1, Salomonsson *et al.*, 1995; Jeng *et al.*, 2004; Delin *et al.*, 2011).

$$\text{MFE (\%)} = \frac{100 * [\text{Nup(waste resource ij) - Nup(control)}]}{\text{Napplied}} \tag{1}$$

MFE = Mineral fertiliser equivalent
Nup = Sum N in biomass from all four harvests (kg N ha^{-1})
Napplied = Total N amount applied with the fertiliser
i = Treatment
j = Amount N applied (150 or 300 kg N ha^{-1})

2.5 Statistical analysis of the results

One-way analysis of variance (ANOVA) was carried out where all treatments were included. For multiple comparisons between treatments the Tukey's studentized range test was applied with a significance level of $P = 0.05$. The means presented followed by the same letter are not statistically different. Additionally minimum significant differences (MSD) are presented for the means. The programme package SAS/STAT (SAS Institute Inc., 1989) was used for the statistical analysis.

3 RESULTS

3.1 Effects of fertiliser treatments on biomass production

The highest loads of minNPK and minN resulted in the highest total yields (Table 8)[5]. There were significant differences between biomass production of plants fertilised with 300 kg N ha^{-1} of minNPK treatments and all combinations of waste based fertilisers.

Application of MBM and CFS resulted in total biomass production at the same significance level. All in all total yields were lower after MBM and CFS fertilisation than after minN and minNPK treatments of the same N amount for all loads and combinations, but there were no significant differences between the waste resources and mineral fertiliser amendments for the lower loads (150 kg N ha^{-1}).

[5] See Appendix III: Results: Total biomass production for a diagram about total biomass production (kg DM ha^{-1}) of all treatments.

None of the Dynea compost treatments had a significant effect on biomass production at any time and neither Dynea 2009 nor Dynea 2004 resulted in significant differences in comparison to the unfertilised control with regards to the total yield. Only the effect of the highest load of Dynea 2004 (300 kg N ha^{-1}) was significantly different from the unfertilised reference treatment. Application of Dynea 2004 resulted generally in higher yields than Dynea 2009, but there were no significant differences between fertilisation effects of the two types of compost.

Application of BWA alone also resulted in equally low yield as the unfertilised control reference. In combination with waste-based N-rich products, there was no significant fertilisation effect of BWA in comparison to the same treatment without BWA.

In general, yields tended to increase with doubled fertiliser N amounts (150 kg N ha^{-1} to 300kg N ha^{-1}). The highest amounts of mineral fertiliser applications (300 kg N ha^{-1} minN and minNPK) were significantly different from the lower amounts in their effect on plant production. Load-based yield differences were, however, not significant for any of the combinations of waste resources.

At the time of the first harvest plants had produced only little biomass with the result of very low yields in general[6]. Especially minN treatments were poorly established and had scarce biomass production. The highest load of minN + BWA (300 kg N ha^{-1}) gave the lowest yield during the first harvest. 150 kg N ha^{-1} CFS without BWA and 300 kg N ha^{-1} minNPK resulted in the highest yields during the first harvest but they were only significantly different from the badly established minN + BWA (300 kg N ha^{-1}) treatments.

During the second harvest minNPK treatments of the highest load (300 kg N ha^{-1}) clearly resulted in the highest biomass production among all treatments. MinNPK treatments were significantly different from all other treatments except for the highest load of CFS mixed with BWA (CFS + BWA, 300 kg N ha^{-1}). MinN treatments of the lowest load (150 kg N ha^{-1}) resulted in biomass production at the same level as all MBM and CFS treatments. 300 kg N ha^{-1} minN treatments had poorer fertilisation effects than equivalent lower loads (150 kg N ha^{-1}) but differences were not significant.

During the third harvest, plants in pots with the highest loads of minN (300 kg N ha^{-1}) were well developed and resulted in the highest yields. They were significantly different from equivalent lower loads of minN (150 kg N ha^{-1}) and all plants fertilised with waste resource combinations.

[6] See Appendix III: Results: Biomass production throughout the season for diagrams about biomass production of all treatments at the time of each harvest (kg DM ha^{-1}).

MinNPK applications still resulted in higher yields than all combinations of waste resources with the same N amount but differences between minNPK and MBM or CFS treatments of the same load were not significant.

The fourth harvest was also characterised by low biomass production in general. Also during the last harvest the highest loads of minN treatments (300 kg N ha^{-1}) clearly resulted in the highest yields, and biomass production after fertilisation with 300 kg N ha^{-1} minN was significantly different from all other treatments. Low load minN treatments (150 kg N ha^{-1}) resulted in plant biomass at the same level as all other treatments. At times of the fourth harvest, treatments with MBM and CFS resulted in higher yields than analogous minNPK treatments but differences between plants fertilised with the waste resources and mineral compound fertiliser were not significant (Table 8).

Table 8: Biomass production (kg ha^{-1}). Results refer to pooled samples per treatment.

Fertiliser	Amount applied	1st harvest	2nd harvest	3rd harvest	4th harvest	Total
Unit	kg N ha^{-1}	kg DM ha^{-1}	kg DM ha^{-1}	kg DM ha^{-1}	kg DM ha^{-1}	kg DM ha^{-1}
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, $P < 0{,}05$		455	1242	1076	555	1965

MSD = minimum significant difference. See Abbreviations for an explanation of the other abbreviations.

3.2 Effects of fertiliser treatments on nutrients in soil and plant biomass

The highest N contents in plant material were measured in plants that received minN or minNPK fertilisation (Figure 1, Table 10). N uptake in control treatments indicated that approximately 39 kg N ha^{-1} mineralised from the soil organic matter. N mineralisation from the soil organic matter enabled N uptake in excess of N applied with the fertiliser after minNPK and minN treatments. All mineral fertiliser amendments resulted in mineral fertiliser equivalents lower than 100% except for 150 kg N ha^{-1} minN and minN + BWA, where excessive N uptake either can be explained by higher N mineralisation than in control pots or errors in measurement. Differences in N uptake between minNPK and minN (150 kg N ha^{-1}) are, however, not significant.

After MBM and CFS fertilisation, plants took up less N than after mineral fertiliser treatments of the same N amount, but differences were only significant for 300 kg N ha^{-1} treatments (Figure 1, Table 10). MBM had a relative N uptake of 49-73%, mineral fertiliser equivalents of CFS were between 48-59%. Relative N uptake decreased for MBM and CFS treatments with increasing loads.

None of the Dynea compost treatments were significantly different from the control with regards to N uptake in biomass. Dynea 2009 had a relative N efficiency of 3-11%, for Dynea 2004 mineral fertiliser equivalents between 16-28% were calculated (Figure 1)[7].

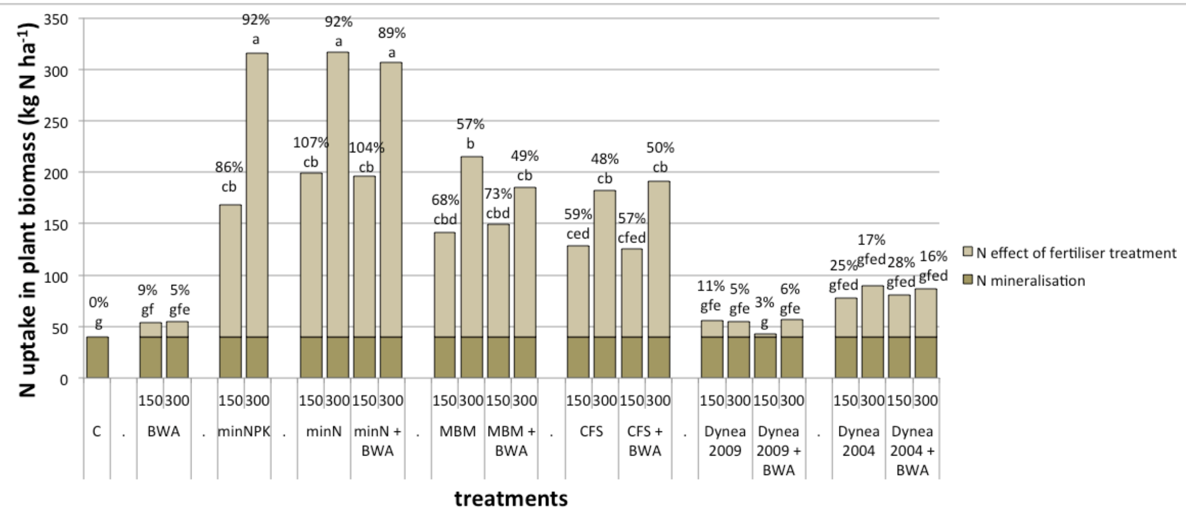

Figure 1: Total N uptake in plant biomass as kg N ha^{-1}. Percentages refer to mineral fertiliser equivalents, letters refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for an explanation of the abbreviations.

[7] See Appendix III: Results: Calculation of mineral fertiliser equivalents.

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

Exploitation of plant available P was best by plants fertilised with CFS, which had the highest P uptake measured as kg P ha^{-1} for all loads and combinations also in comparison to minNPK (Table 10). Also MBM and minN treatments resulted in significantly higher P uptake than the unfertilised control. None of the Dynea compost treatments had significant effects on P contents in biomass. Plants that received BWA fertilisation in addition to N-rich waste tended to have somewhat higher P uptake but differences between treatments with and without BWA were not significant[8].

MinN treatments resulted in low P concentration in plant biomass throughout the season. Especially biomass of the first two harvests showed low P concentrations in biomass with 1.8 to 2.0 g P kg^{-1} for minN and minN + BWA (150 kg N ha^{-1}, 300 kg N ha^{-1}) by times of the second harvest. According to Bergmann (1993) ryegrass is undersupplied with P if contents are falling below 3.5 g P kg^{-1}. From the third harvest onwards, P concentration in plant material increased but first at the time of the fourth harvest 150 kg N ha^{-1} minN treatments had concentrations of 3.9 and 4.5 g P kg^{-1}, whereas 300 kg N ha^{-1} minN treatments were still undersupplied with P (results are not shown).

Only MBM treatments increased P-AL values substantially. After all other treatments P-AL values were more or less unchanged in comparison to soil conditions at the beginning of the experiment (Table 9)[9]. All MBM amendments except for 150 kg N ha^{-1} MBM, increased P-AL in the soil from low to high values according to Norwegian classification (Bioforsk, 2003). With regards to P-AL in the soil, MBM treatments were significantly different from all other treatments except for CFS + BWA (300 kg N ha^{-1}), which also increased P-AL values in the soil considerably. BWA fertilisation also had a positive effect on P-AL values in the soil but significant differ-

[8] See Appendix IV: Discussion: P fertilisation effect of BWA.
[9] See Appendix III: Results: Effects of fertiliser treatments on P-AL contents in the soil for diagram.

ences were only found for 150 kg N ha^{-1} MBM and for 300 kg N ha^{-1} CFS when treatments with and without BWA were compared.

Total K balances, which were calculated based on fertiliser application and K removal by plant biomass, were negative for all treatments except for BWA, Dynea 2009 + BWA and Dynea 2004 + BWA (300 kg N ha^{-1}), where plant growth and hence K uptake probably was reduced by N deficiency (Table 7, Table 9). The highest K removal was measured for plants fertilised with the highest load of minNPK treatment (300 kg N ha^{-1}), which removed 412 kg K ha^{-1}, an amount that is 5 times as high as K fertiliser recommendations for Norwegian pastures (Bioforsk, 2003). K concentration of plant biomass was higher than required minimum amounts for all treatments with 4.2 g K 100 g^{-1} DM in the pooled sample of the unfertilised control treatments during the first harvest (results are not shown). According to Bergmann (1993) ryegrass is sufficiently supplied with K if concentrations are higher than 2.5 g K $(100g)^{-1}$ DM. K contents in plant material were generally decreasing with time but were still high at the time of the last harvest with a mean value of 3.3 g K 100 g^{-1} DM in the unfertilised controls. BWA fertilisation tended to have a positive effect on K uptake in plant biomass but there were no significant differences between treatments with and without BWA of the same load regarding K uptake (Table 10).

All treatments resulted in reduced K-AL values in the soil at the end of the experiment in comparison to initial values (Table 5, Table 9)[10]. Only the highest loads of CFS + BWA and BWA (300 kg N ha^{-1}) kept K-AL values in the soil at a constant level. In general, K-AL values in the soil were highest in pots that received BWA fertilisation only, and BWA treatments of both loads were significantly different from the unfertilised control with regards to K-AL values in the soil.

Amounts of Ca-AL and Mg-AL in the soil were generally reduced in comparison to the beginning of the experiment. Ca-AL values were highest in pots that received BWA, MBM or minN fertilisation. Mg-AL-values showed the same trend as Ca-AL values but were in contrast to Ca-AL not increased by minN fertilisation (Table 9). Ca and Mg in plant material mainly followed biomass response functions (Table 10).

[10] See Appendix III: Results: Effects of fertiliser treatments on K-AL contents in the soil for diagram.

Table 9: Content of P-AL, K-AL, C-AL and Mg-AL in the soil as mg (100g)$^{-1}$ soil after the experiment.

Fertiliser	Amount applied (150 kg N ha^{-1} + 120 kg K ha^{-1})				Amount applied (300 kg N ha^{-1} + 240 kg K ha^{-1})			
Nutrient	P-AL	K-AL	Ca-AL	Mg-AL	P-AL	K-AL	Ca-AL	Mg-AL
Unit	mg 100g^{-1} soil	mg 100g^{-1} soil	mg 100g^{-1} soil	mg 100g^{-1} soil	mg 100g^{-1} soil	mg 100g^{-1} soil	mg 100g^{-1} soil	mg 100g^{-1} soil
Control	3	3	247	13	3	3	247	13
BWA	5	7	267	15	5	8	270	16
minNPK	3	4	247	13	4	4	249	13
minN	3	4	264	13	3	4	265	12
minN + BWA	4	5	290	15	4	6	277	14
MBM	7	4	267	14	11	4	262	13
MBM + BWA	12	6	287	16	13	6	287	16
CFS	4	4	255	13	6	3	259	13
CFS + BWA	6	5	277	15	10	9	292	18
Dynea 2009	3	3	245	13	3	3	244	12
Dynea 2009 + BWA	4	6	257	14	4	7	261	15
Dynea 2004	3	3	251	13	3	4	243	12
Dynea 2004 + BWA	4	6	268	15	5	7	267	16
MSD, *P* < 0,05	3	3	34	3	3	3	34	3

MSD = minimum significant difference. See Abbreviations for an explanation of the other abbreviations.

Table 10: Uptake of total N, P, Ca and Mg in plant biomass as kg ha^{-1}.

Fertiliser	Amount applied (150 kg N ha^{-1} + 120 kg K ha^{-1})					Amount applied (300 kg N ha^{-1} + 240 kg K ha^{-1})				
Nutrient	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Unit	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	39	7	79	16	4	39	7	79	16	4
BWA	53	9	106	20	5	54	9	114	21	6
minNPK	168	16	258	51	13	315	23	412	74	21
minN	199	14	254	53	16	316	18	317	75	24
minN + BWA	195	15	290	52	15	306	19	350	68	22
MBM	141	15	230	42	13	215	19	265	59	17
MBM + BWA	149	17	259	43	13	185	18	282	51	15
CFS	128	18	227	41	12	182	24	255	53	16
CFS + BWA	125	19	240	37	11	190	24	315	48	14
Dynea 2009	56	9	110	21	6	54	9	112	21	6
Dynea 2009 + BWA	43	8	90	10	8	56	9	114	22	6
Dynea 2004	77	11	146	29	5	90	12	160	30	8
Dynea 2004 + BWA	81	11	155	28	8	86	11	166	28	7
MSD, *P* < 0,05	74	6	85	16	5	74	6	85	16	5

MSD = minimum significant difference. See Abbreviations for an explanation of the other abbreviations.

3.3 Effects of fertiliser treatments on soil pH

Effects of fertiliser treatments on soil pH were generally low as a result of buffering reactions in the experimental soil, which was characterised by relatively high amounts of organic material and a high clay content (Table 5, Table 4).

The lowest pH values were measured for minNPK treatments (300 kg ha^{-1})[11]. The highest pH values were measured for minN treatments (150 kg ha^{-1}) in combination with BWA. Differences in pH between minN treatments with BWA and minNPK were significant for both loads (Figure 2).

BWA fertilisation tended to result in higher pH values in the soil than the unfertilised control and all fertiliser combinations with BWA showed a trend of higher soil pH than equivalent fertiliser treatments without BWA. However, BWA treatments were not significantly different from the control with regards to pH. Differences in soil acidity between treatments with and without BWA were not significant in any case.

Higher fertiliser loads always seemed to result in lower pH values. Also differences in pH with regards to load were not significant. It seems as BWA application buffered effects of waste applications on soil acidity and reduced differences in pH related to fertiliser load (Figure 2).

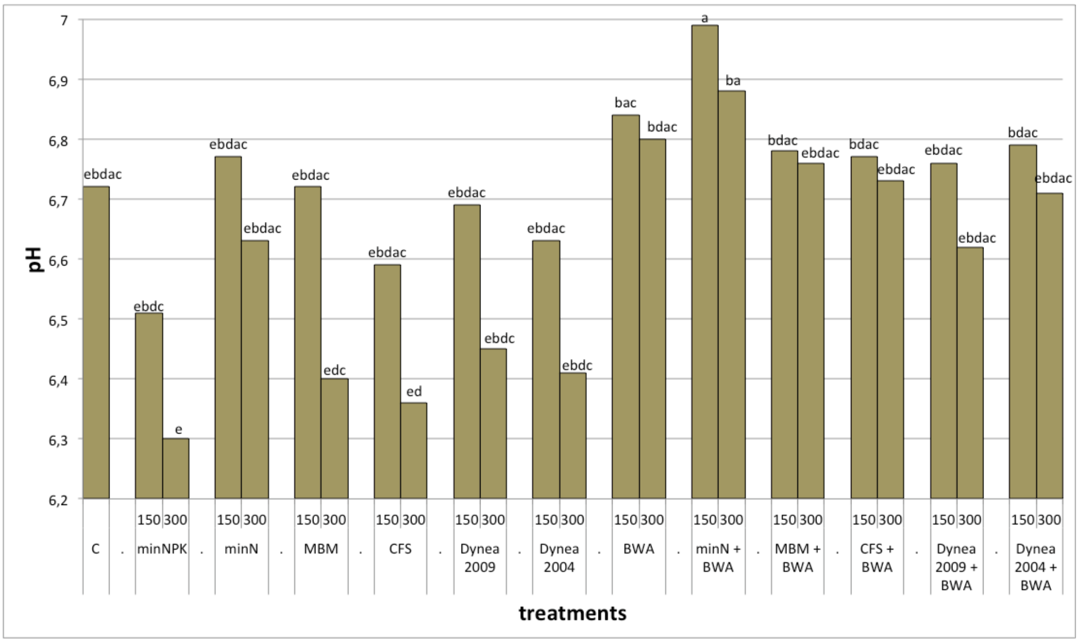

Figure 2: pH values in soil after the experiment. The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for an explanation of the abbreviations.

[11] See Appendix IV: Discussion: Effect of minNPK on pH for a discussion on the acidifying effect of mineral N fertiliser.

4 DISCUSSION

4.1 Plant available N and mineralisation rate of N-rich waste resources

The results suggest that availability of mineral N was the key limiting factor to plant growth during the present experiment. Mineral N treatments resulted therefore in the highest total biomass production (Table 8). There was also a clear response of biomass growth to increasing N amounts and chemical analyses of the soil indicate that plants took up all available mineral N. This is in agreement with previous studies on fertilisation values of waste residues as presented by Boen and Haraldsen (2011) who ran an experiment with various composts and biosolids as fertiliser to perennial ryegrass (*Lolium perenne*). Also Haraldsen and Krogstad (2011) found in studies on the efficiency of organic NPK fertilisers that treatments with the highest N uptake were the treatments with the highest biomass production in general. In the present experiment minN treatments resulted in total yields that were not significantly different from plant biomass after minNPK fertilisation. Therefore it seems, as if the soil supplied the crops with sufficient amounts of P and K after all. There were no visual signs of shortage or toxicity of other nutrients and chemical analyses of plant material indicated acceptable supply of all essential elements.

A possible explanation for generally scarce biomass production by the time of first harvest is that germination of grass seeds was harmed as a result of deep seed placement (Table 8).

MBM and CFS treatments resulted in good and even biomass production throughout the season but their fertilisation effects were limited by N mineralisation. N mineralisation seemed to be the determining factor for fertilisation effects of MBM and CFS, as their initial mineral N contents were low (Table 2). Plants that received CFS tended to have a better start than plants that were fertilised with MBM, which can result from slightly higher initial amounts of mineral N in CFS (Table 2, Table 8).

Mineral fertiliser equivalents of MBM and CFS (48-73%) were somewhat lower but within the same range as equivalent values found in previous studies on MBM (Figure 1, Jeng *et al.*, 2004; Delin *et al.*, 2011). Delin *et al.* (2011) suggested that the relative N efficiency of MBM can be as high as 60-80% after a pot experiment, where different waste residues were applied to ryegrass (*Lolium spp.*). According to Jeng *et al.* (2004) mineral fertiliser equivalents of MBM can be 80% or higher during the 1st year after application, but since results of Jeng *et al.* (2004) are based on a field experiment with powdery MBM, a comparison with their findings is of limited value. Pelletized MBM, which was used in the present experiment, seems to result in lower total yield than powdery MBM (Trøite, 2007), as pellets have to moisturise and dissolve before nutrients become available to plants. This is probably the main reason why mineral fertiliser equivalents of MBM were not as high as equivalent values found by Jeng *et al.* (2004). In the experiment run by Haraldsen *et al.* (2011) the combination of pelletized MBM and BWA probably achieved yields at the same level as the equivalent mineral fertiliser treatments because MBM fertiliser amendments were calculated based on an estimated N effect of 80% of Kjeldahl-N, whereas fertiliser levels in the present experiment were calculated based on total N amounts in N-rich waste.

With increasing loads of MBM and CFS their fertilisation effect on biomass production declined (Table 8). Whereas 150 kg N ha^{-1} had fertilisation effects in the same range as equivalent mineral fertilisers, application of 300 kg N ha^{-1} resulted in plant biomass that was significantly lower than biomass production after the addition of 300 kg N ha^{-1} as mineral fertiliser amendments. Similar results were described by Trøite (2007) after studies on different organic fertilisers in a pot experiment with barley (*Hordeum vulgare*). Also results of Haraldsen and Krogstad (2011) indicate that there was a declining course regarding fertilisation effects of N-rich waste resources in their experiment on the efficiency of organic NPK fertilisers. A possible explanation for reduced response to higher loads is that plants and microorganisms compete for oxygen and nutrients when microbial activity increases with increasing amounts of organic fertiliser. Mondini *et al.* (2008) found that mineralisation of MBM considerably triggers microbial activity in the soil. The declining trend of pH values after application of increasing loads of MBM (Figure 2) can also indicate increased microbial respiration. Microbial respiration is associated with release of carbon dioxide that in reaction with water forms carbonic acid, a source of soil acidity (Brady and Weil, 2008). Increased microbial activity with increasing loads of organic material might therefore be the reason why fertilisation effects of MBM and CFS are significantly different from mineral fertiliser amendments for 300 kg N ha^{-1} but not for 150 kg N ha^{-1}.

Probably easily soluble mineral fertilisers (minN and minNPK) would have resulted in lower biomass production if N losses had not been intentionally avoided during the present experiment. Irrigation was adapted to the specific soil characteristics so that denitrification losses were reduced and closed plant-soil system set up by Kick/Brauckman pots prevented nitrate from leaching to deeper soil layers.

Haraldsen *et al.* (2010) found that fertilisation with N-rich waste resources, which require mineralisation of organic N for the nutrient to become available to plants, can potentially reduce nitrate leaching in comparison to mineral fertiliser amendments, where N is easily soluble. In a pot experiment with barely (*Hordeum vulgare*), where different waste residues were compared with mineral fertiliser amendments, all waste residues achieved higher yields than equivalent mineral N treatments as a result of a leaching episode during early plant development (Haraldsen *et al.*, 2010).

On field level up to 50% of N fertiliser that is applied to agricultural fields in the EU is today lost by volatilisation, leaching, soil erosion and denitrification (Roy *et al.*, 2002; Smil, 2011). N efficiency calculations and overall performance of MBM and CFS should therefore not be generalised inconsiderately. A comparison of MBM and CFS with mineral fertiliser amendments under field conditions might be useful to study the actual fertilisation effect of N-rich waste resources.

Dynea composts had poor N fertilisation effects for all loads and combinations resulting in low biomass production throughout the season (Figure 1, Table 8). This shows that organic N in the Dynea composts was rather recalcitrant. Slow N mineralisation is typical for mature compost material (Amlinger *et al.*, 2003; Bar-Tal *et al.*, 2004; Boen and Haraldsen, 2011) and Asdal and Breland (2003) even suggested that mature compost material releases mineral N so slowly that the amount of inorganic N probably is equivalent to plant available N. Based on analyses of chemical properties prior to the experiment 2-5 kg mineral N ha^{-1} and 5-9 kg mineral N ha^{-1} were applied with Dynea 2009 and Dynea 2004, respectively (Table 2, Table 7). Obviously these amounts were far from sufficient to supply plants with the N needed if inorganic N is set equal to the composts' N fertilisation values.

Somewhat higher initial amounts of mineral N in Dynea 2004 material are a possible reason for why mineral fertiliser equivalents of the older material tended to be higher than equivalent values for Dynea 2009 (Figure 1). However, also growth-inhibiting effects of the younger material cannot be excluded, as soil processes were not studied in detail and as detailed information about the industrial compost material of Dynea is missing.

If undesirable influences of young Dynea compost on growing conditions can be excluded, the results suggest that Dynea composts can generally be applied in 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 fertilisers, which are defined as a products with the key task of supplying plants with nutrients (Norwegian Ministry of Agriculture, 2003, appendix 1).

4.2 P fertilisation effect of waste resources

The results suggest that P-AL amounts in the experimental soil were high enough to hide P effects of waste-based fertiliser products on biomass production, as P removal by plants with the harvested biomass was in an acceptable range also for minN treatments (Table 10, Bioforsk, 2003).

With MBM and CFS enormous amounts of P were applied, as fertiliser amendments were calculated based on total N contents in waste resources regardless N:P ratios. MBM and CFS had narrow N:P ratios of 2 and 4, respectively. Pots that received MBM or CFS fertilisation were therefore fertilised with total P amounts equivalent to 37 to 214 kg total P ha^{-1} (Table 7), whereas 16 kg P ha^{-1} are commonly recommended fertilisation amounts to grassland in Norway (Bioforsk, 2003).

All in all, CFS tended to result in higher P uptake than MBM, even though higher P amounts were applied with MBM (Table 10, Table 7). This is in agreement with studies of Haraldsen and Krogstad (2011) who found somewhat higher P uptake by wheat (*Triticum spp.*) after fertilisation of composted fish sludge of codfish hatcheries than after MBM amendments. It seems therefore as if availability of P is higher in CFS than in MBM. Chemical properties of the material suggest that a higher ratio of P in CFS is immediately available to plants in comparison to MBM, if P-AL values are set equal to plant-availability of the nutrient (Table 2). Also, the results of the present experiment indicate that the P fertilisation effect of CFS is independent from pH, whereas Jeng *et al.* (2006) suggest that MBM-P is more soluble in acidic than in neutral or alkaline soils. Previous studies on MBM show that plant availability of P in meat and bone meal is dependent on the ratio of the P containing fractions bone and meat (Jeng *et al.*, 2006). Organic P in the meat fraction can easily be taken up by plants, whereas P in the bone fraction is present as $Ca_5(PO_4)_3OH$ requiring H^+ to become plant available. The soil in the present experiment was almost neutral (Table 5). It seems therefore as if CFS had better pre-conditions than MBM with regards to availability of P in the material.

Surprisingly, MBM fertilisation resulted in an increase of soluble P in the plant-soil system (P-AL in the soil and P taken up by the plants) that was higher than the amount of total P applied with the material for all loads and combinations. P-AL values in soils increased up to 4.5-fold after fertilisation with MBM in comparison to the unfertilised control (Table 9). Similar effects of MBM on plant available P were observed by Andersen (2008) when MBM was applied to barley (*Hordeum vulgare*). Also after the experiment of Andersen (2008) there were higher amounts of P in the plant-soil system than P applied with the fertiliser product at the beginning of the experiment (Andersen, 2008). According to the results, MBM might be a more valuable alternative P fertiliser than believed so far, if P availability in MBM is higher than P-AL analyses let assume and if MBM, additionally, has a stimulating effect on the P equilibrium in the soil.

Several studies have already reported residual P effects of MBM on soils in comparison to balanced fertilisation with phosphate rock (Jeng *et al.*, 2006; Ylivainio *et al.*, 2007). Jeng *et al.* (2006) and Jeng and Vagstad (2008) recommended therefore that MBM should be fertilised with respect to the crop's P- rather than N-demand, and that early spring and late autumn application should be avoided. To avoid that phosphate leaching and erosion of particulate P turn MBM and CFS into an environmental challenge, repeated application two seasons after each other was not recommended (Jeng *et al.*, 2006; Jeng and Vagstad, 2008). Based on the results of the present experiment it seems as these recommendations have to be revised and that P fertilisation should also be avoided the second and possibly the third year after MBM application. However, more research has to be done on the actual P fertilisation effect of MBM.

BWA also tended to supply crops with plant available P (Table 9, Table 10). Still, the assumption is likely that plants that received minN + BWA fertilisation were initially deficient in P. Probably initial P deficiency after minN + BWA treatments was as a result of a temporary pH increase.

If pH values are higher than 7, P will precipitate with Ca to form insoluble calcium-phosphates, which cannot be taken up by the plants (Brady and Weil, 2008). Figure 2 suggests that BWA increased soil pH. Alkaline effects of BWA are in accordance with findings of Schiemenz *et al.* (2011), who found significant increases of soil pH when different biomass ashes were applied to Italian ryegrass (*Lolium multiflorum* var. *italicum*) in a pot experiment with sandy loam. In the present experiment fertiliser applications were applied at a thin layer 5 cm under soil surface together with the seeds. The alkaline effect of highly reactive BWA was therefore probably distinct in this area at the beginning of the experiment, and the little amount of soluble P in the soil was fixated by precipitation.

It seems as though plants that received minN + BWA fertilisation had overcome P deficiency by the time of the third harvest. With time, pH probably decreased as a result of buffering reactions in the soil. Furthermore, root systems of plants fertilised with minN + BWA were well developed at the time of the third harvest. According to Aasen (1997) and Grant *et al.* (2001) plants often compensate P deficiency with enhanced root growth to stimulate uptake of scarce P in the soil solution. Since N applied with minN was still available in the pots, minN treatments had the possibility to catch up with plants that had been sufficiently supplied with P also during plant development, and to outperform them with the highest biomass production during the last two harvests (300 kg N ha^{-1} minN, Table 8).

Results of the present experiment indicate therefore that BWA is better suited for acidic than for alkaline soils as also suggested by Knapp and Insam (2011), who reviewed literature on the effect of ashes on soil properties.

Scarce P supply from the soil might also have had negative impacts on plant development after minN treatments (Table 8). Poor establishment after minN treatments can, however, most likely mainly be traced back to inhibited germination. Placement of calcium nitrate together with the seeds probably caused a high concentration of the salt NO_3^- in the area surrounding the seeds resulting in negative impacts on germination.

4.3 K fertilisation effect of waste resources

It seems as potential K fertilisation effects of BWA were hidden by sufficient K supply from the soil even though soil K-AL values were only moderate (Table 2, Bioforsk, 2003). Øgaard *et al.* (2002) found no yield response of plants on K-fertilisers when soil-K exceeded 8 mg K-AL $(100g)^{-1}$. Soil analyses prior to the experiment showed that the soil contained 8.2-8.7 mg K-AL $(100g)^{-1}$ (Table 5), an amount that apparently is high enough to result in luxury uptake of K by Italian ryegrass. Furthermore, K-uptake by minN treatments even exceeded readily available K (K-AL) in the soil (calculations are based on a soil density of 1.2 g cm^{-3} and soil depth of 20 cm) indicating that reserve-K became available to plants. Also Øgaard *et al.* (2002) pointed out that K-AL analysis might not be satisfactory to assess plant available K in soils.

Even though sufficient K supply from the soil made K fertilisation effects of BWA on biomass production invisible, there were significant differences between K-AL values in soils of BWA treatments and the unfertilised control. Similarly, Ferreiro *et al.* (2011) found increased K levels in soils of mountain pastures fertilised with wood ashes. In accordance with results of Haraldsen and Krogstad (2011) it is likely that BWA has a long term K fertilisation effect when K contents in the soil are depleted, which could become obvious by an experimental approach covering several years. Moreover, sandy soils with poor K buffer are possibly more appropriate for the assessment of BWA as K fertiliser than clayey soils that have the ability to release considerable amounts of reserve-K from interlayers (Brady and Weil, 2008).

4.4 Outlook

The aim of the present experiment was to study NPK fertilisation effects of combined waste resources with the purpose to contribute to the development of a fertiliser product that can substitute conventional compound fertilisers. In addition to fertilisation effects, however, there are several other impacts, which determine if waste-based fertiliser products can be a sustainable alternative to artificial fertilisers. Sustainability assessments require methods with a systemic instead of reductive approach.

Emergy analyses are energy analyses of products or services where direct and indirect energy inputs of all kinds are transformed into the same unit (Rydberg and Haden, 2006). By conducting an emergy analysis, energy required for production and transport of low dry matter waste-based NPK fertiliser material can therefore be compared to synthetic fertiliser products. Life cycle analysis (LCA) is a tool to study environmental impacts of products taking into account all associated up- and downstreams from production to transport, consumption and disposal. LCA allows therefore the comparison of waste-based fertiliser products with conventional synthetic NPK fertilisers with regards to influences on the environment (Brentrup *et al.*, 2004).

If the definition of sustainability, however, not only encompasses ecological aspects but also economic values and social impacts, emergy or life cycle analyses alone are inappropriate for sustainability assessments of waste-based fertiliser products. Combining multiple criteria analyses with emergy analyses or LCA is a possibility to involve multiple perspectives in sustainability studies of waste-based NPK fertiliser products and to conduct a complete evaluation of this forward-looking concept (Brulliard and Boyle, 2009).

Regardless of sustainability assessments, a major determining factor for a farmer's decision-making and choice between alternative and conventional fertiliser products will probably be the price. Increasing costs of artificial fertilisers and political measures to reduce agricultural impacts on the environment have already resulted in declining use of synthetic NPK fertiliser products in Norway during the last couple of years (Aase, 2011). In the future, fertiliser prices will most likely continue to rise as P and fossil fuel reserves are getting depleted. Fertiliser products that are based on waste residues might then become attractive alternatives not only for organic farmers. And when limited resources are coming to an end, we will possibly have to re-close natural nutrient cycles by returning waste to agricultural land as a matter of course.

5 CONCLUSION

The pot experiment with Italian ryegrass as experimental crop indicated that availability of mineral N was the key limiting factor to plant growth. None of the N-rich waste resources had the potential to supply plants with appropriate amounts of mineral N. Fertilisation with meat and bone meal and composted fish sludge resulted in acceptable overall performance but narrow N:P ratios were the reason why the fertiliser combinations could not supply the plants with sufficient amounts of N in comparison to P. Dynea composts showed slow N mineralisation and poor fertilisation effects, as typical for mature compost material and are hence rather to be classified as soil conditioners than as fertilisers. Further studies have to be done on the optimisation of N fertilisation values of alternative NPK fertilisers before waste-based fertiliser products are ready for commercial production.

Results of the present experiment showed furthermore that meat and bone meal can substantially increase the amount of plant available P (P-AL) in the plant-soil system. On a global scale this means that meat and bone meal could function as a valuable P fertiliser with the potential to substitute mineral P fertilisers. With respect to the plants' needs, however, composted fish sludge seems to be a more appropriate ingredient in alternative NPK fertiliser products because of reduced effects on residual P in the soil, good availability of P in the material, and independence of P on soil pH, as well as a wide N:P ratio and relatively high initial amounts of mineral N.

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7 APPENDIX I: BACKGROUND

7.1 Challenges connected to the use of artificial N and P fertiliser

Continuing today's agricultural practices, some of the inevitable future challenges will be accumulation of reactive N in the atmosphere and other negative impacts of N fertiliser on the environment, additionally to limitations of fossil fuel energy and depletion of easily minable P reserves (Dawson and Hilton, 2011).

Anthropogenic N fixation by the Haber-Bosch-process is today accounting for the largest share among activities that intensify the natural biogeochemical N cycle (Smil, 2001). Various negative environmental impacts of N fertilisation are connected to the fact that the use efficiency of fertiliser amendments is usually not higher than 50% (Roy *et al.*, 2002; Smil, 2011). Since pre-industrial times, anthropogenic activities have so far released the same amount of reactive N that naturally circulates between terrestrial ecosystem and the atmosphere (Chapin *et al.*, 2002). Only if the plant nutrient is completely denitrified into innoxious N_2, fertilisation with artificial N fertiliser is harmless to the environment (Bakken and Dörsch, 2007). Incomplete denitrification on the other hand results in emission of the reactive mineral N forms N_2O, NO or NO_2 (Smil, 2011). N_2O, which has been accumulating in the atmosphere since the introduction of artificial N fertiliser to agriculture in the middle of the 20th century, contributes considerably to the destruction of the stratospheric ozone layer and to the greenhouse effect, since it is 300 times more reactive than CO_2 (Chapin *et al.*, 2002; Matson *et al.*, 2002; Bakken and Dörsch, 2007). Emitted NO and NO_2 can be transported over long distances in the atmosphere causing unintended fertilisation at deposition (Tilman *et al.*, 2002). Additionally, emission of NO_x is one of the main reasons for acid rains. Also volatilisation of NH_3 results in acid rain when ammonia turns into NH_4^+ in reaction with water or in acidification of soils at deposition. Leaching and erosion of NO_3^- causes acidification of soils and eutrophication of marine coastal areas (Smil, 2011).

Artificial N fertilisers do not only cause considerable environmental impacts, also enormous amounts of energy are needed to fix the macronutrient from the vast pool of non-reactive N in the air (Dawson and Hilton, 2011). According to Hansen and Serikstad (2011) the production of each kg N fertiliser requires the input of 1 kg oil. While today's agroecosystems are highly dependent on external energy, known sources of fossil fuel are gradually being depleted. According to de Almeida and Silva (2009) peak oil will most likely be reached before 2012, Kerr (2011) suggests that we might already have passed peak oil. Over the long run renewable energy might replace fossil fuel as an external energy source to the anthropogenic fixation of N. However, with increasing production costs for energy and hence for the production of N fertiliser, food prices will certainly rise.

Just as fossil fuel, also phosphate rock, mined for the production of P fertiliser, is limited and in danger of being depleted (Dawson and Hilton, 2011). In comparison to energy, which can be replaced by renewable forms of energy, there are no alternatives to phosphate rock. Once P is accumulated in the ocean's sediments it is lost and cannot be recovered with current techniques (Smit *et al.*, 2009). P-containing marine sedimentary rocks will return to terrestrial ecosystems only after millions of years (Chapin *et al.*, 2002). Smit et al. (2009) took world population growth, increased use of biofuels and future diet changes into consideration when they calculated P reserve exhaustion and concluded that today's economically exploitable P reserves will last another 75 years. According to a review of Cordell *et al.* (2009) easily minable phosphate rock will be exhausted within 50-100 years. Smil (2000) suggests that global P reserves will last another 70 years. Different studies propose different numbers of years until phosphate rock will be depleted. Thinking in terms of sustainability, the exact time rate does not matter. The fact is, P is limited and quality of remaining P reserves has already been declining resulting in increasing costs of P fertilisers over the last years (Cordell *et al.*, 2009).

A close look at inevitable challenges connected to today's fertilisation practices demonstrates that a change of thinking is essential to ensure future food supply. Agroecosystems can only be sustainable if the input of artificially produced fertilisers is kept to a minimum in favour of application of natural ecosystem principles and recycling of waste resources (Gliessman, 2004).

7.2 Challenges connected to the use of waste as fertiliser

Looking at recirculation of waste to agriculture from multiple perspectives, there are several challenges that prevent many farmers from applying them to agricultural land yet.

Minimum requirements regarding material quality are one issue that limits the use of waste resources on agricultural land. Governmental regulations set restrictions based on maximum contents of heavy metals, environmental poisons and pesticides in the material. Additionally, it is required that organic fertiliser material is sanitised and stabilised: Stabilisation reduces undesirable odours and potential pollution of the environment; by sanitisation infection of contagious diseases to humans, animals and plants through the organic material is avoided (Norwegian Ministry of Agriculture, 2003, §10). Treatment of the organic material to fulfil the requirements can, however, be cost-intensive.

Costly transport of waste resources can be another obstacle: Organic waste resources usually possess low dry matter contents and are bulky. If transport is unviable, disposal of organic waste will be more attractive. Different treatments have the potential to decrease material volume and to enable economically viable transport of waste material but they will again increase the cost of the fertiliser material.

For farmers, practical application of waste resources can be an issue. Bulky material hinders even application and hence equal nutrient supply. Powdery, dusty products are exposed to wind and can be lost by erosion. Pelletized products on the other hand can be spread with conventional fertiliser distributors, but the process of pelletizing increases the costs of the material.

Additionally, often there is a lack of knowledge about the actual fertilisation and liming effect of each of the waste resources. The amount of the nutrients that will become available for plants during the growing season, is dependent on several factors such as the quality of the material but also external influences as soil temperature and biochemical as well as textural properties of the soil (Cayuela *et al.*, 2008). The temporal variation of mineralisation of nutrients in the material can hence be remarkable. Detailed information about each single waste resource has to be gained regarding nutrient content, decomposition and mineralisation dynamics and hence the fertilisation effect to turn waste into a valuable resource.

Unbalanced NPK ratio in the material compared to the plants' needs is another challenge regarding the use of waste as fertiliser (Haraldsen and Krogstad, 2011). The present experiment was therefore set up to test combinations of N- and K-rich waste resources regarding their fertilisation effects and to assess their potential to overcome the challenge of unbalanced NPK ratios in waste material.

7.3 Decomposition of organic matter and nutrient mineralisation dynamics

Substituting mineral fertilisers by waste resources requires knowledge about the biological processes in the soil, which determine plant availability of nutrients in organic material. Understanding of decomposition, mineralisation and immobilisation processes is therefore important to supply crops with nutrients at the right time and to reduce the risk of nutrient losses to the environment (Breland, 1992).

Decomposition is the physical and chemical transformation of organic material into CO_2, nutrients and complex organic compounds that are unaffected by further microbial breakdown (Chapin *et al.*, 2002). The first step of decomposition of organic material is leaching of water-soluble organic compounds and mineral ions as K^+. Soil animals increase the specific surface of organic material when they split it into smaller pieces. They also distribute the material and transport it to different soil layers. Microorganisms secrete extra-cellular enzymes to initiate chemical breakdown and extract energy form the material when they break down carbon molecules to CO_2. After satisfaction of microorganisms' need, nutrients are released to the soil system during the process of mineralisation. If microorganisms are, on the other hand, in lack of energy, they will take up mineral nutrients instead and compete with plants for N and P during the process of immobilisation (Breland, 1992; Chapin *et al.*, 2002).

Mineralisation of N is tightly linked to C mineralisation and the decomposition of organic material (Flavel and Murphy, 2006). When microbes emit extra-cellular enzymes to the environment to decompose organic material, N is released as dissolved organic N (DON). When microbes break down DON to make use of the carbon skeleton as source of energy, NH_3 is released, which is in reaction with water transformed to NH_4^+ (Chapin *et al.*, 2002). Dependent on external conditions NH_4^+ is nitrified to NO_3^- and further denitrified to N_2, N_2O, NO or NO_2, lost by volatilisation, taken up by the plants or immobilised by microorganisms (Breland, 1992). A rule of thumb says that N mineralisation occurs at C:N ratios < 20:1. Immobilisation happens at C:N ratios > 20-30. Immobilised N will first be released when the surplus of C is used up, when microorganisms die and when their body mass is breaking down (Havlin *et al.*, 2005). Gross N mineralisation is a measurement for the entire amount of N being released of organic material. Net N mineralisation of organic matter measures the actual amount of mineralised N in the soil. The main aspects determining net mineralisation are total C and N content of the soil, long term mineralisation and mineralisation-immobilisation turnover (Flavel and Murphy, 2006). Organic amendments can therefore both increase and reduce the amount of plant available N in soil systems.

P mineralisation is triggered by the enzyme phosphatase, which cuts ester bonds in organic matter to release phosphate (PO_4^{3-}). The release of plant and microbial phosphatases is stimulated by low soil phosphate contents. The mineralisation of P is hence not as strongly linked to the decomposition of organic matter as the mineralisation of N (Chapin *et al.*, 2002). Mineralisation of P occurs at a N:P ratio of < 200. At N:P > 300 P is immobilised (Havlin *et al.*, 2005). Availability of P to plants is restricted to a small pH range. The optimal availability of P is at a pH of around 6.5. In acid and calcareous soils P precipitates as secondary minerals or is adsorbed to oxides and clay minerals. In acid soils P forms stable molecules with Fe or Al, in neutral and calcareous soils P precipitates with Ca and Mg (Havlin *et al.*, 2005). Therefore, mineralisation of organic P may result in immediate immobilisation by adsorption or precipitation of the nutrient.

The decomposition rate of organic matter is strongly dependent on the quality of material. Quality can be described as the physical and chemical composition of the material. Commonly, the C:N ratio has been used as an indicator to assess quality of decomposable material. However, this model is very simplified and is not true in all cases. According to Gale *et al.* (2006) C:N ratios might work as indicator for decomposition rates of fresh crop residues or manure, but cannot predict decomposition rates of processed material in a sufficient manner. Other determining factors for the quality of organic matter are 'size of molecules, the types of chemical bonds, the regularity of structures, the toxicity and nutrient concentrations' (Chapin *et al.*, 2002). Substrates as sugar and aminoacids are therefore generally faster mineralised than cellulose and hemicellulose or lignin and cutin (Chapin *et al.*, 2002).

Regarding decomposition and mineralisation dynamics in soils one has to be aware of the temporal dimension. The different phases of decomposition of organic matter and immobilisation take place simultaneously dependent on the original mass remaining at each point of time and by-products produced by the microbes (Chapin *et al.*, 2002). Flavel and Murphy (2006) found that net mineralisation of untreated poultry manure was not different from stable compost material but timing of mineralised N varied considerably between the treatments.

Apart from the material's quality there are several external factors that influence the mineralisation process. According to Chapin (2002) decomposition processes are usually determined by the physical environment with the aspects temperature, moisture, soil properties and soil disturbance and by microbial composition and abundance.

Successful fertilisation with waste residues is in a higher degree dependent on knowledge about processes in the soil than application of mineral fertilisers, which supply plants with easily soluble nutrients.

8 APPENDIX II: WASTE RESOURCES

8.1 Bottom wood ash

Biomass ash is a solid, inorganic residual product that accumulates as end-product during thermal combustion activities (Knapp and Insam, 2011) and that contains mainly Ca, but also K and Mg as well as low amounts of P and a variety of micronutrients (Steenari *et al.*, 1999). BWA is one of the products of combustion in grate-fired boilers where biomass is burnt on a grate under constant supply of air. BWA is the material that falls through the grid, whereas fly ash is the material that can be collected in a flue gas cleaning filter. In grate-fired boilers, BWA accounts for about 90% of the end product, approximately 10% of the material is fly ash. BWA usually contains low amounts of heavy metals as they commonly have low melting points. Therefore, heavy metals tend to accumulate in the fly ash (Emilsson, 2006). If BWA is separated from fly ash, BWA will commonly contain so low amounts of heavy metals that the material is well suited as fertiliser to agricultural land.

Ashes have been used as fertiliser since early agriculture and are the oldest mineral fertilisers (Schiemenz *et al.*, 2011). Today they are still of considerable importance in traditional agroecosystems with slash and burn activities all over the world (Gliessman, 2007).

Due to high Ca contents biomass ashes seem to be especially suitable as fertiliser to acid soils (Knapp and Insam, 2011). Wood ashes usually have a pH at around 9 to 13 (Emilsson, 2006). According to Risse (2002), who reviewed use of wood ashes on agricultural land in the USA, the calcium carbonate equivalent (CCE) of different wood ashes varies between 25-60%, according to Emilsson (2006) the CCE of burnt ashes is between 50-70%.

Mozaffari *et al.* (2002) pointed out the potential K fertilisation effect of ashes after application of alfalfa stem ash to corn (*Zea mays*), which resulted in increased K and decreased Mg concentration in plant biomass. In their studies ash application also increased the amount of exchangeable cations as K^+ in the soil (Mozaffari *et al.*, 2002). This was either due to the application of K with the ashes, or due to increased pH and to base cations displacing readily available K^+ on exchange sites of soil particles (Ohno, 1992; Mozaffari *et al.*, 2002). Also Erich (1991) tested plant availability of K in wood ash in an experiment with corn (*Zea mays*) as experimental crop and found that K availability was similar to the availability of the macronutrient in artificial fertiliser.

According to Mozaffari *et al.* (2002) and Schiemenz *et al.* (2011) application of ash also has the potential to increase the amount of plant available P in soils. Increase of P is either caused by application of the element with the ash or due to raised pH and increased solubility of soil P reserves in originally acidic soils (Mozaffari *et al.*, 2002; Schiemenz *et al.*, 2011). Schiemenz *et al.* (2011) suggested that the P fertilisation effect of BWA might be as high as that of artificial P fertilisers. Therefore, extraction of P by citric acid seems to be the appropriate method to study plant-available P in BWA (Schiemenz *et al.*, 2011).

A drawback according the application of biomass ashes to agricultural land is their varying quality in terms of heavy metals and hazardous environmental poisons such as radioactive substances and organic pollutants. Suitable combustion techniques, separation of different ash fractions and clean parent material are necessary requirements to biomass ashes to avoid pollution of agricultural soil when they are used as fertiliser (Emilsson, 2006; Knapp and Insam, 2011).

The Norwegian regulations that control the use of organic fertiliser also regulate the use of wood ashes on agricultural land (Norwegian Ministry of Agriculture, 2003, appendix 4). Regulations are based on the amount of heavy metals in the material on a dry matter basis. In ashes the amount of heavy metals is increased compared to the original organic material, the regulations restrict the use of ashes on agricultural fields therefore strongly (Haraldsen *et al.*, 2011).

8.2 Meat and bone meal

MBM is a rest product from industrial slaughtering operations. MBM contains high amounts of organic matter and considerable concentrations of N (8%) and P (5%) additionally to Ca (10%) (Jeng *et al.*, 2006). Due to high contents of easily plant available N and long-lasting P fertilisation effects, MBM represents fertiliser material that is also well suited for organic farming activities (Salomonsson *et al.*, 1994; Salomonsson *et al.*, 1995; Fredriksson *et al.*, 1997, 1998; Ylivainio *et al.*, 2007).

Most of N in MBM is in an organic form. However, the low C:N ratio (< 4) implies that the material is potentially fast mineralised (Jeng *et al.*, 2004). If conditions are optimal, around 50% of the material is mineralised only four days after application (Cayuela *et al.*, 2008; Mondini *et al.*, 2008). In an experiment of Cayuela *et al.* (2008) the maximum respiration rate measured as CO_2 production was reached after 24 h for swine MBM and 48 h for bovine MBM. The process was therewith clearly faster in comparison to other organic fertilisers as farmyard or chicken manure and crop residues, which contain plant structures being more resistant to decomposition (Cayuela *et al.*, 2008). According to studies of Mondini *et al.* (2008) on decomposition of MBM in soil, it seems as if MBM contains high quantities of easily degradable amino acids and polypeptides, which can readily be used by microorganisms as source of energy and C. In their experiment the abundance of aerobic bacteria, which grow fast in presence of readily available substrate, increased. Mondini *et al.* (2008) found also that microorganisms use lipids in organic material as source of energy. MBM that was not defatted, mineralised faster than material that had been defatted in the factory prior to soil application (Mondini *et al.*, 2008).

According to Jeng *et al.* (2004) the relative N efficiency of MBM can be 80% or higher during the 1st year after application when compared to mineral fertiliser. Salomonsson *et al.* (1994; 1995) assessed the effectiveness of MBM as N fertiliser to wheat (*Triticum spp.*) and found that the plants can utilise containing N compounds better than N in pig slurry and that N in MBM was utilised as well as urea-N. Fredriksson *et al.* (1997, 1998) found positive effects of MBM on the baking performance and dough characteristics of wheat.

Jeng *et al.* (2006) estimated the relative P efficiency of MBM to be 50% in comparison to phosphate rock fertilisers. P in MBM has considerable residual effects, additional P fertilisation is therefore not recommended during the year after application (Jeng *et al.*, 2006). Ylivainio *et al.* (2007) assume that around 20% of P in MBM is available immediately after application. During their experiment more than 60% of P was released within a 3-years period which emphasizes the long-term effect of P in MBM (Ylivainio *et al.*, 2007).

The N:P ratio in MBM is with a value of < 2 (Jeng *et al.*, 2004; Jeng *et al.*, 2006; Ylivainio *et al.*, 2007; Jeng and Vagstad, 2008) rather low in comparison to the amounts of N and P plants require. In Norway farmers are recommended to supply an average pasture with fertiliser equivalent to N:P ratios of 6-9 (Bioforsk, 2003). This means that fertiliser levels of MBM amendments that are adapted to the plants' N-need exceed the plants' requirements for P four fold. If MBM fertiliser rates are based on the plants' N-demand, there is a substantial surplus of P in the soil being exposed to leaching and erosion and bearing a risk for eutrophication of nearby water bodies (Jeng *et al.*, 2006). If the fertiliser amount is calculated to meet the plants' P-demands, additional N fertiliser will have to be applied to avoid N deficiency (Jeng and Vagstad, 2008). There are only negligible contents of K in MBM. If MBM is applied as the main source of nutrients, K fertiliser has to be applied additionally if K deficiency in crops should be avoided.

According to Norwegian regulations, stabilised MBM of category 3 material can be used as fertiliser to all crops except to grasslands that are mowed or pastured. In combination with other fertiliser material, however, MBM can also be applied to grasslands (Norwegian Ministry of Agriculture, 2002, § 4; Norwegian Ministry of Fisheries and Coastal and Norwegian Ministry of Agriculture, 2007). Each year an amount of 30.000 t of MBM of category 3 is produced in Norway (Haraldsen *et al.*, 2011).

8.3 Composted fish sludge (Global Enviro International AS)

Fish sludge is the accumulation of faeces and feed residues on the ground of hatcheries and fish farms where fish are bred for human consumption.

Fishery and aquaculture activities are of considerable economic importance for Norway. Only the export of oil and gas is more profitable for the country (Andersen, 2011). Since the 1980s aquaculture activities have increased and in 2009 the income of fish farming exceeded those of fishery with an amount of 11.000 million Norwegian kroners (Steinset, 2009).

Salmon is the fish species that is produced most of in Norway (Steinset, 2009). The process of salmon production starts in fresh water hatcheries where eggs are artificially inseminated and where fish hatch. The young salmons are then raised in fresh water before they are moved to open sea cages in fjords, where they are fed until they reach a market size of 4-5 kg (del Campo *et al.*, 2010).

At the same time as the economic importance of aquaculture activities grows, the amount of accumulated sediments in hatcheries increases. In 2010 around 40.000-50.000 t of sediments were collected in Norwegian hatcheries for salmon and trout. The material is characterised by a low dry matter content of 10% and contains around 4-5% N and 2-3% P (Blytt *et al.*, 2011). Effluent of hatcheries is commonly discharged directly into the sea (Norwegian Ministry of Fisheries and Coastal, 2008, §59) unless companies are put upon a request to treat waste water prior to discharge (pers. comm. Lund, 2011). Currently only small amounts of Norwegian fish sludge are spread on agricultural fields after the material is mixed with local farmyard manure, or stabilised with lime (Gebauer and Eikebrokk, 2006; Blytt *et al.*, 2011).

In several experiments the fertilisation effect of fish sludge has been studied and compared to the fertilisation value of animal manure. Both untreated and anaerobically treated fish sludge seem to have the potential to result in higher biomass production and N and P uptake than conventional animal manure (Gebauer and Eikebrokk, 2006; Uhlig and Haugland, 2007). Salt contents in sludge originating from seawater fish farms can pose problems because of uptake of sodium (Na) and other salts by the crops (Teuber *et al.*, 2005), and fish sludge from freshwater hatcheries seems therefore to be better suited for application on agricultural land than sludge collected in fjords.

In Norway there are two main drawbacks regarding the use of fish sludge from hatcheries in agriculture. It is doubtful whether the material is in accordance with the Norwegian law, which requires sanitation and stabilisation of organic fertilisers (Norwegian Ministry of Agriculture, 2003, §10). Additionally, the bulky material has to be transported from fish hatcheries, which are commonly located along the west coast, to arable land in the eastern inland. The transport of the sludge, which is characterised by low dry matter content, considerably increases the cost of the organic fertiliser (pers. comm. Lund, 2011).

To overcome these drawbacks and to increase the suitability of fish sludge as organic fertiliser, sludge of smolt hatcheries of the company Aasen Settefisk AS has experimentally been treated in a composting reactor that the company Global Enviro International AS originally developed for the treatment of food waste. During the composting process in the reactor, fish sludge is heated until desirable dry matter is reached before the material is homogenised under aerobic conditions. After decomposition in the reactor, fish sludge has turned into a brown, dry, sanitised powder with unproblematic odour. Increased dry matter content makes transport of CFS viable.

Characteristics of CFS allow the assumption that its fertilisation effect is similar to that of MBM (Blytt *et al.*, 2011). After processing, the material is not fully stabilised and is hence expected to mineralise fast after application to soil. Even though much N is lost as NH_3 during the composting process, the material still contains around 7% N, which is mainly present in organic form. C:N ratio in the material is with 7 (see Table 2) almost as low as in MBM (5, see Table 2). 2% of CFS is P, which is almost fully plant available. The ratio of N:P-AL (4, see Table 2) can be compared with the N:P-AL ratio of MBM (5, see Table 2). As in all types of sludge, there are low contents of K in CFS since K is leaching with water due to its soluble nature (Blytt *et al.*, 2011).

Haraldsen and Krogstad (2011) tested composted fish sludge of codfish hatcheries in a biennial pot experiment with barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*) as experimental crops. The fish sludge was composted by the same reactor physiology as sludge from smolt hatcheries that was used in the present experiment. Its fertilisation value was compared with MBM, composted catering waste and mineral fertiliser treatments. CFS fertilisation resulted in yields as high as MBM, and after application of 160 kg N ha^{-1} CFS, there was no significant yield difference to equivalent mineral fertiliser treatments (Haraldsen and Krogstad, 2011). In an experiment of Haraldsen *et al.* (2010) composted catering waste that also was processed in a composting reactor of the company Global Enviro International AS, resulted in the same yield as equivalent mineral fertiliser treatments after application of 160 kg N ha^{-1}.

However, more research has to be done on the question whether the decomposition of composted fish sludge is cost-effective and whether the production of composted fish sludge as organic fertiliser material is profitable in the large scale.

The use of CFS as fertiliser on agricultural land in Norway is regulated by the Norwegian regulations that control the use of organic fertilisers (Norwegian Ministry of Agriculture, 2003).

8.4 Neutral and acid compost (Dynea ASA)

The international company Dynea ASA, which is located in the chemical industry business, mainly produces plastic material and organic chemistry products.

In some of their processes an organic, liquid discharge is produced that is rich in N. This effluent is cleaned biologically through a microbial filter. During the cleaning process N-rich microbial biomass is created. This by-product is mixed with bulking material in form of wood chips or bark and is composted in windrows outdoors. Considerable amounts of N are lost from the material when NH_3 volatilises during the thermophilic stage of the composting process. Due to the N-rich parent material, Dynea ASA compost still contains 7-8% N, which makes the material possibly interesting as an organic fertiliser. However, there are only low contents of P and K in the material (Table 2).

If Dynea ASA compost is stored, an acidification process will happen: polymers of formaldehyde break down into formic acid, which lowers the pH gradually to around 3.5. Additionally, considerable amounts of NO_3^- in the stabile compost material are at risk of being leached, a process, which acidifies the material even further. In the present experiment both neutral (pH 7.3), younger material of the year 2009 and acidic (pH 3.5), older material of the year 2004 were used. The objective of testing both compost types was to assess the influence of low pH in older material on germination and biomass production.

In the present experiment Dynea composts were included in the experimental design to test their effect on plant growth and the potential to market the material as fertiliser. Fertilisers are commonly defined as products with the key task to supply crops with nutrients. Composts are usually characterised by reduced fertilisation effects but typically have positive influences on physical, chemical or biological soil properties and are hence rather classified as soil conditioners than as fertilisers (Norwegian Ministry of Agriculture, 2003).

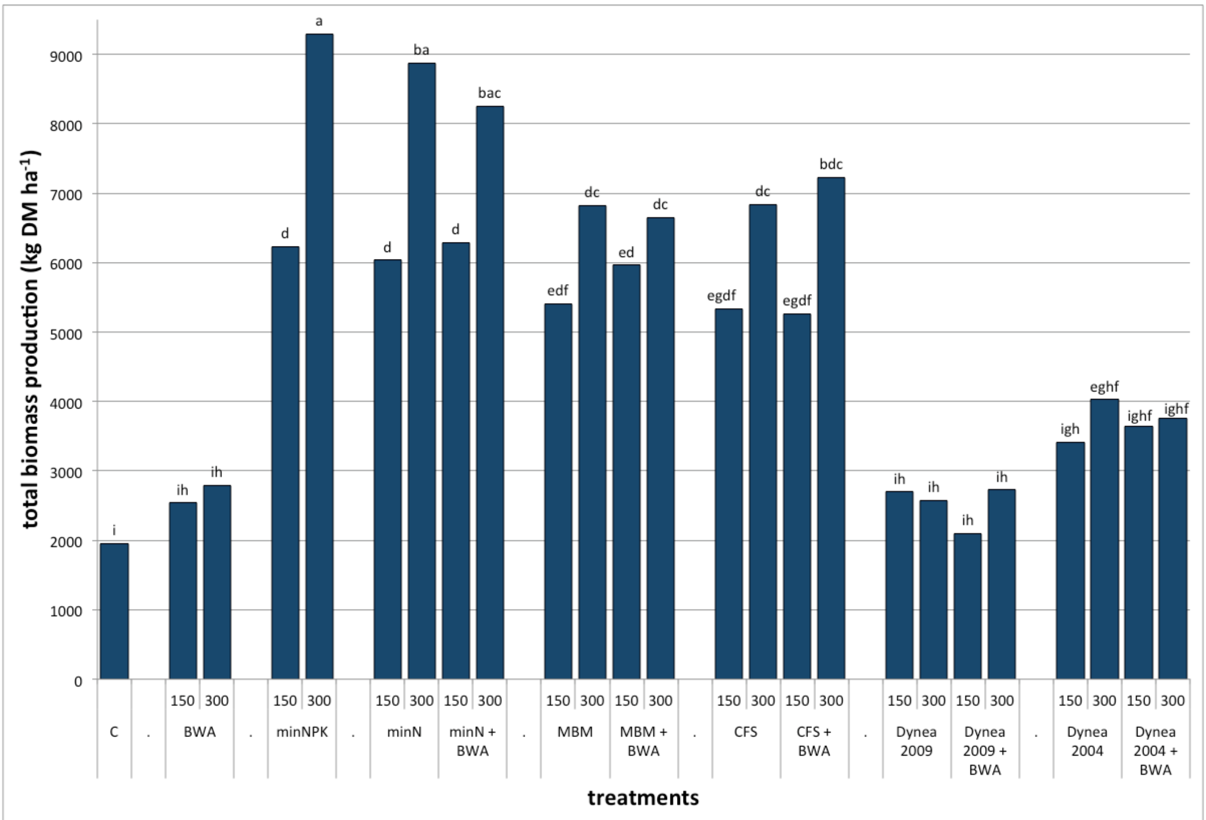
According to Bar-Tal *et al.* (2004), who tested NPK uptake of irrigated wheat (*Triticum spp.*) after different compost applications, N net mineralisation of compost cannot supply the cereal with sufficient amounts of N. Also Asdal and Breland (2003) found that mineralisation rates of stable composts were so low that inorganic N contents in the material seem to be equivalent to plant available N. Boen and Haraldsen (2011) tested the effect of increasing amounts of composted biowaste on urban greening with perennial ryegrass (*Lolium perenne*) as the experimental crop. They found that there was only moderate growth during the establishment and two growing seasons after application. The results of Boen and Haraldsen (2011) indicate that large amounts of biowaste compost can be added to soil without strong effects on plant growth. In their experiment 6-11% of N in the material was plant available during the first growing season. During the second season only up to 3% of N in the material was taken up by the plants (Boen and Haraldsen, 2011). In a review on N mineralisation dynamics in biowaste Amlinger *et al.* (2003) also concluded that at most 5-15% N in the material are released throughout the first growing season, 2-8% of N is plant available during the season after application. In an experiment by Haraldsen *et al.* (2000) application of compost did not have a better effect on plant growth than the unfertilised control unless it was mixed with sewage sludge, even though C:N ratios of composting materials were comparatively low with 14 and 25.

Dynea compost material was, however, expected to result in higher fertilisation effects than conventional composts due to comparatively high contents of N and, consequently, low C:N ratios (Table 2).

The use of Dynea composts as fertiliser on agricultural land is also regulated by the Norwegian regulations that control the use of organic fertilisers (Norwegian Ministry of Agriculture, 2003).

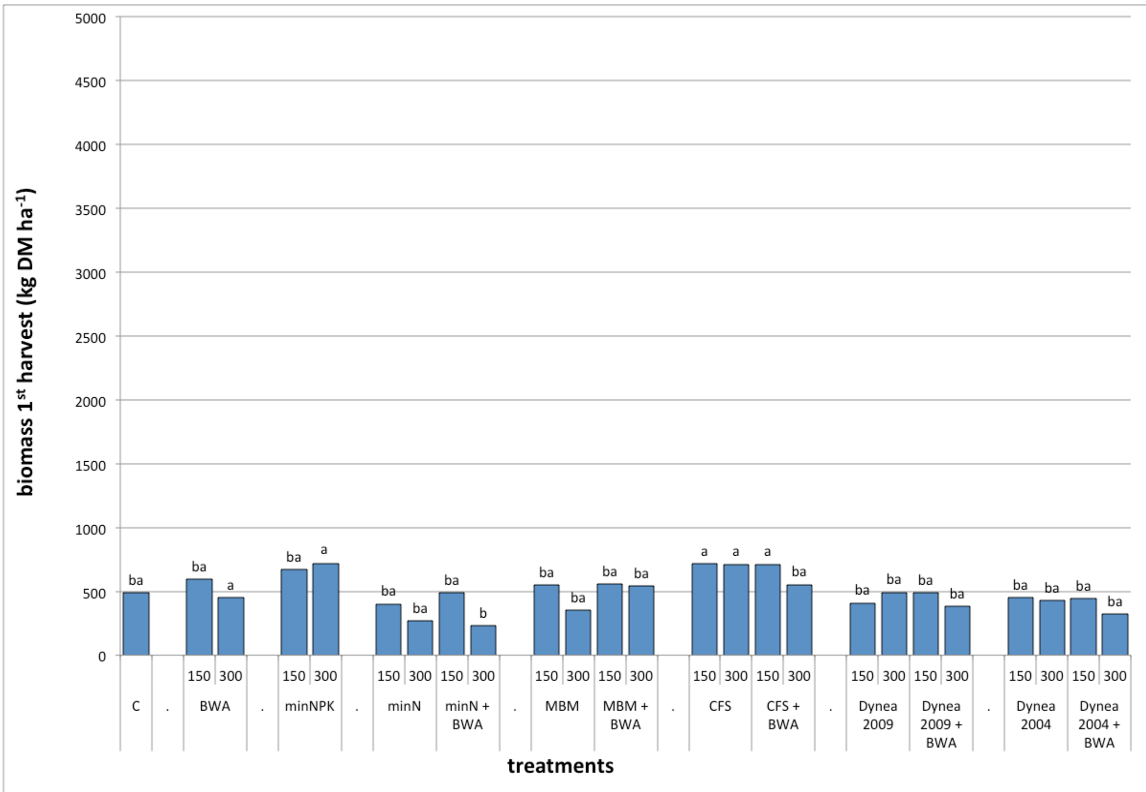
9 APPENDIX III: RESULTS

9.1 Total biomass production

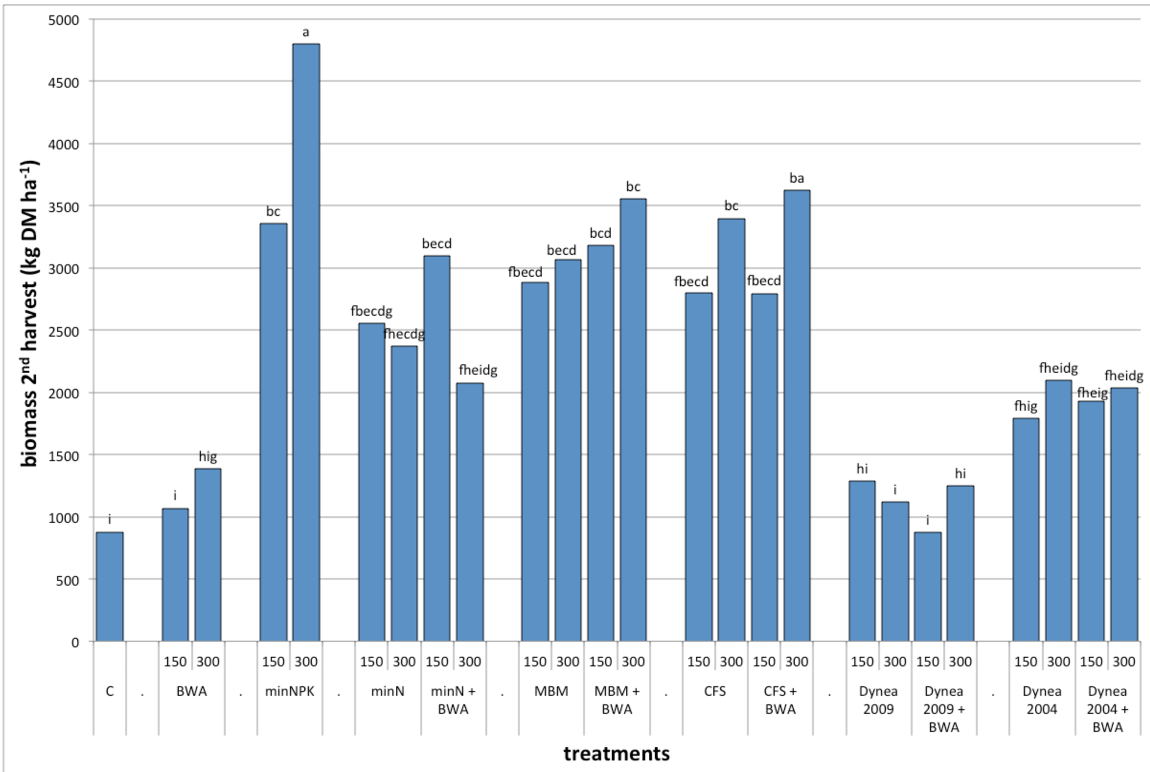


Total biomass production (kg DM ha^{-1}) for all treatments. The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.

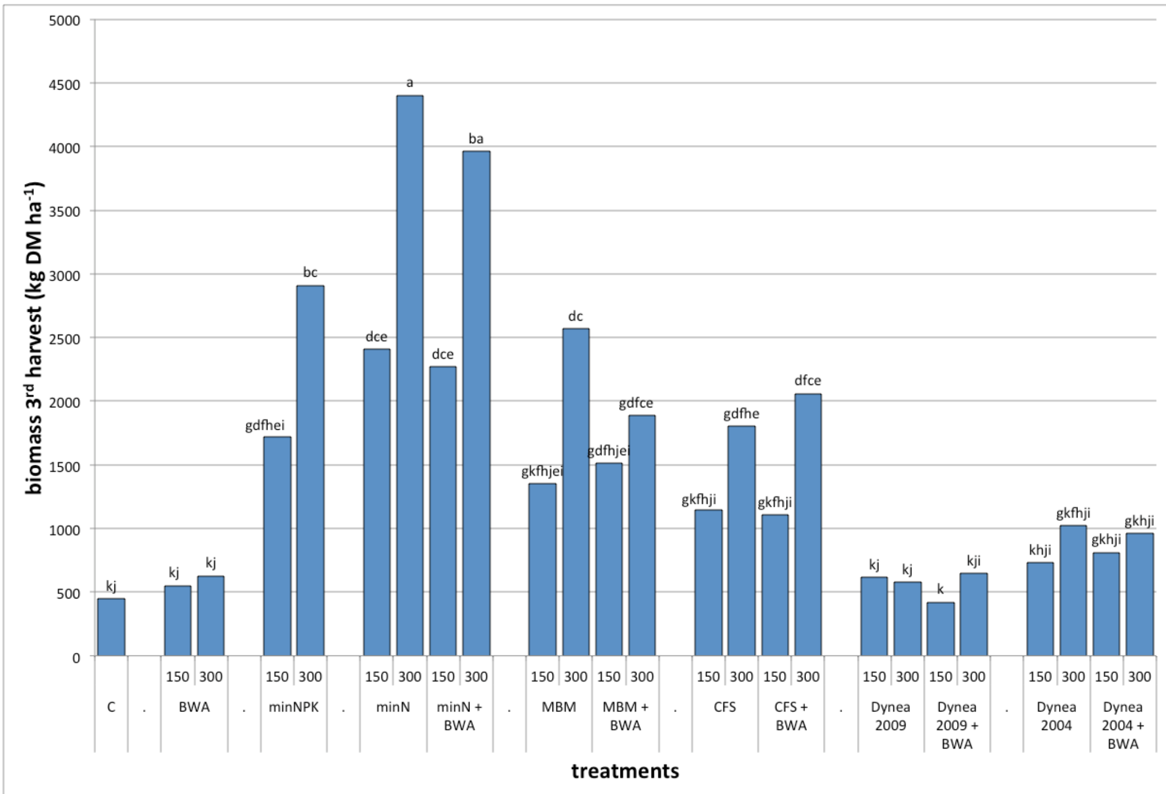
9.2 Biomass production throughout the season



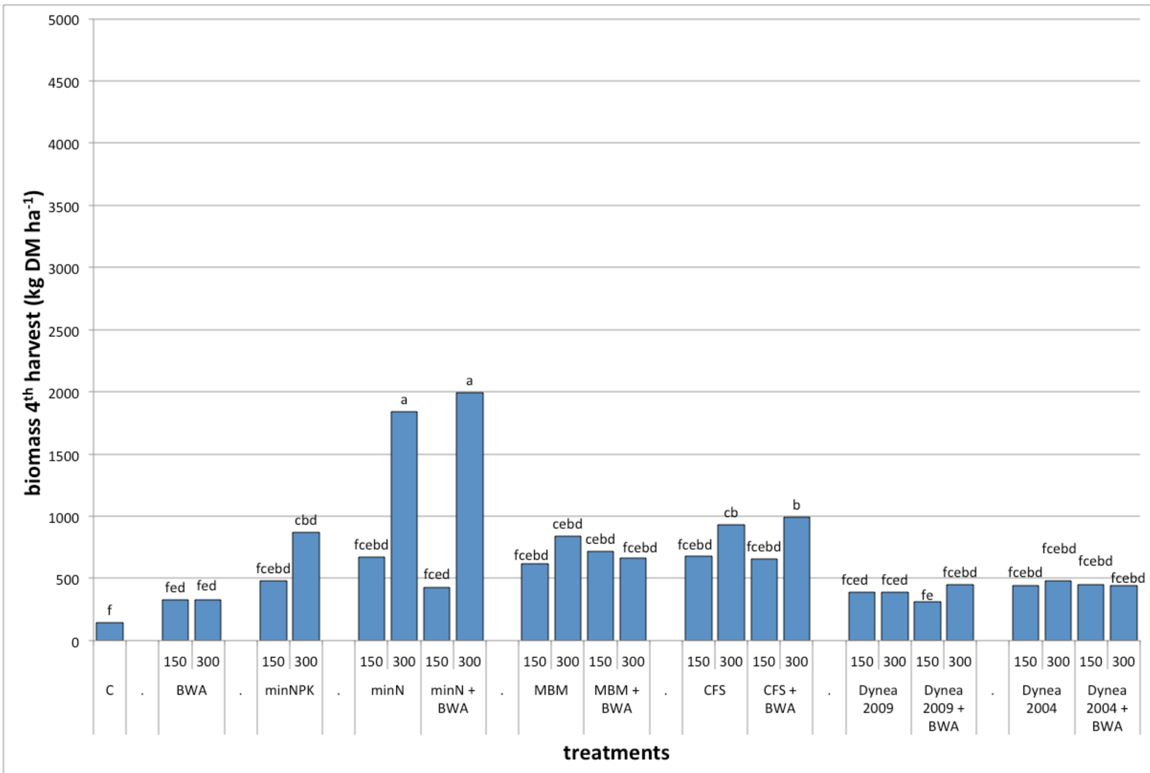
Biomass production for all treatments at the time of the first harvest (kg DM ha^{-1}). The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.



Biomass production for all treatments at the time of the second harvest (kg DM ha^{-1}). The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.

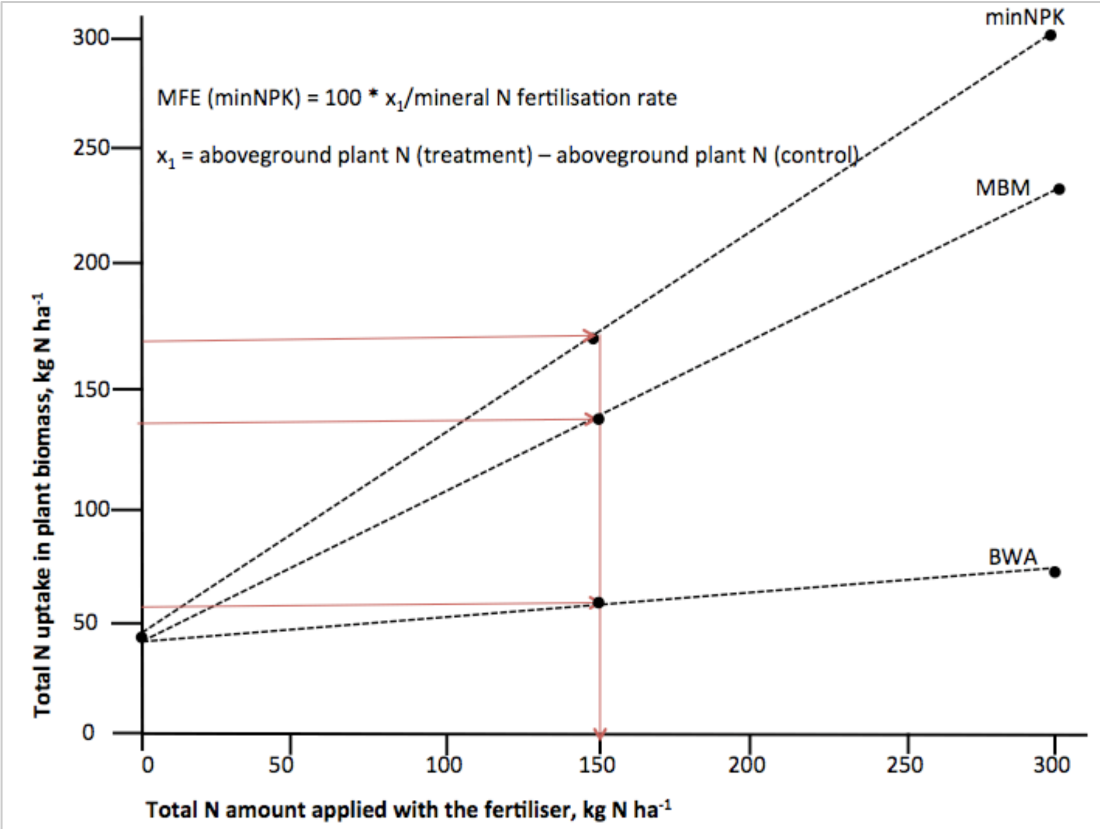


Biomass production for all treatments at the time of the third harvest (kg DM ha^{-1}). The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.



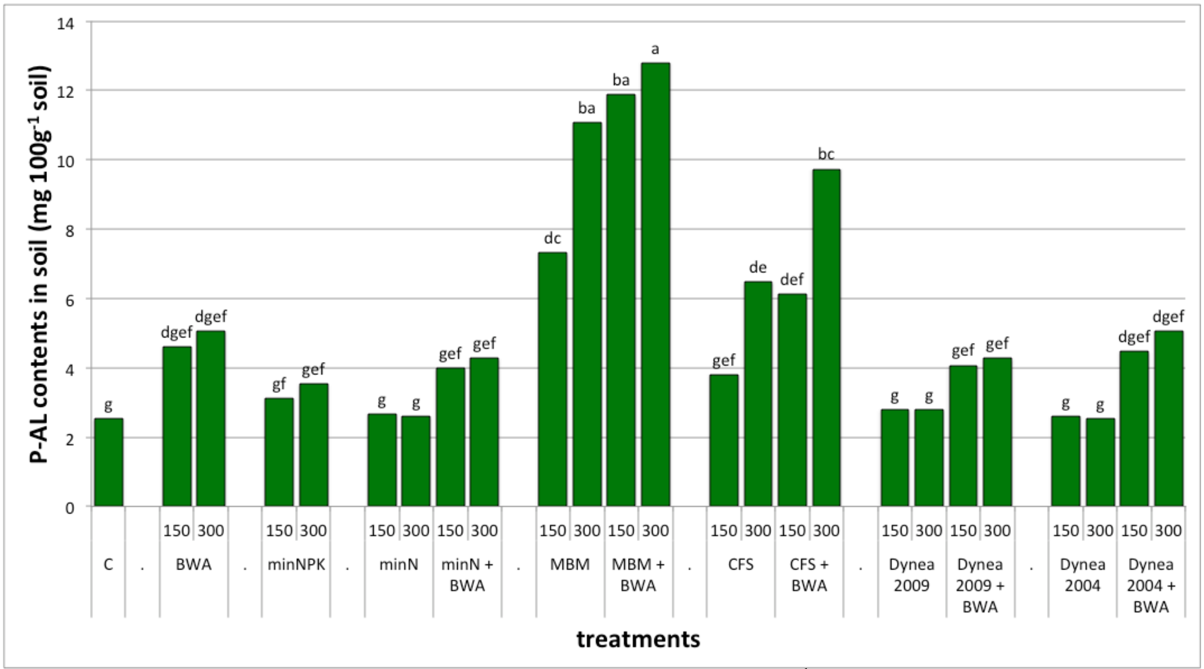
Biomass production for all treatments at the time of the fourth harvest (kg DM ha^{-1}). The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.

9.3 Calculation of mineral fertiliser equivalents



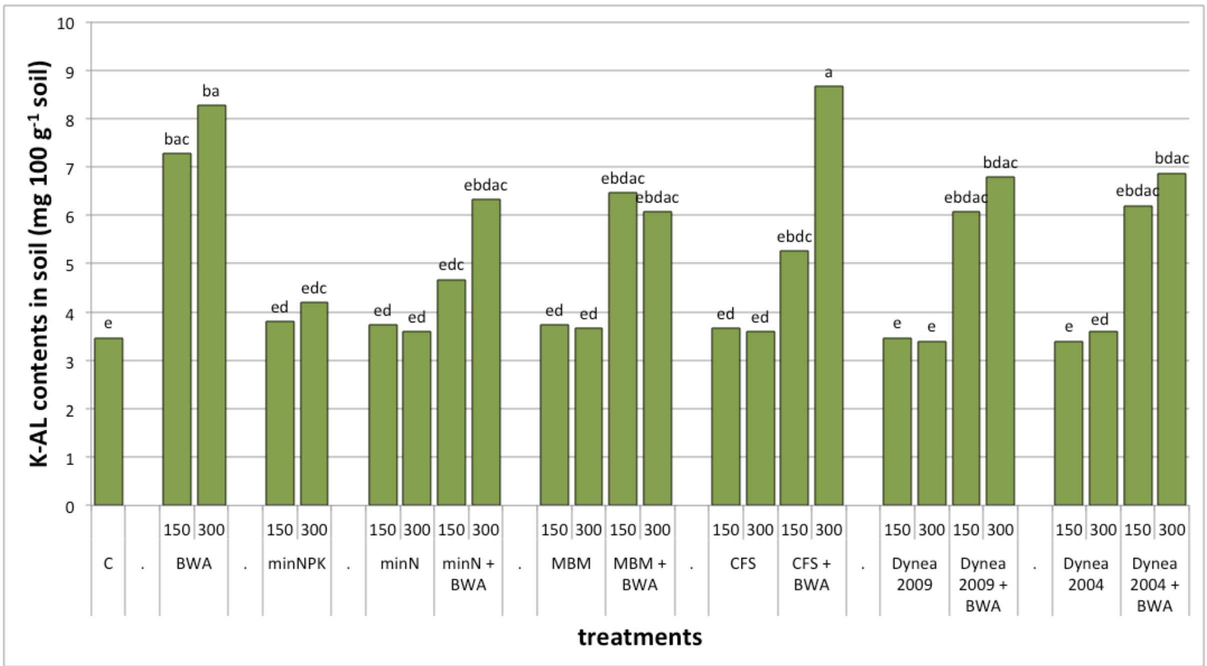
Calculation of mineral fertiliser equivalents of minNPK, MBM and BWA (examples). Mineral fertiliser equivalents represent the amount N taken up by the crop minus N mineralisation from the soil organic matter expressed as rate of total N applied (modified after Delin *et al.*, 2011).

9.4 Effects of fertiliser treatments on P-AL contents in the soil



Effects of fertiliser treatments on P-AL contents in the soil (mg (100g)$^{-1}$ soil). The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.

9.5 Effects of fertiliser treatments on K-AL contents in the soil



Effects of fertiliser treatments on K-AL contents in the soil (mg (100g)$^{-1}$ soil). The etiquettes refer to Tukey's test (one-way ANOVA model including all treatments). See Abbreviations for abbreviations.

10 APPENDIX IV: DISCUSSION

10.1 P fertilisation effect of BWA

BWA fertilisation tended to increase on P contents in plant material and P-AL in soils (Table 9, Table 10) even though there were no significant differences between BWA treatments and the unfertilised control with regards to P-AL values in the soil. Results are in accordance with studies of Schiemenz *et al.* (2011) who found that application of different ashes has the potential to increase P-pools in the soil. Likewise, Haraldsen and Krogstad (2011) found that minN + BWA fertilisation resulted in somewhat increased P uptake in barley (*Hordeum vulgare*) in comparison to minN application alone.

In the present experiment P fertilisation effects of BWA were, however, unexpected. All in all BWA contained 1.7 g P $(100g)^{-1}$ of which only 11% were predicted to be plant available, if P-AL analyses are set equal to plant available P in the material (Table 2). In accordance with results of Haraldsen and Krogstad (2011) the present experiment indicates that P fertilisation effect of BWA is higher than P-AL analyses let assume. P-AL analyses, a method adapted to soil characteristics, are run on ICP-AES after P extraction with a solution of 0.1 M ammonium lactate and 0.4 M acetic acid buffered to a pH of 3.75 (Egnér *et al.*, 1960). Possibly, pH 12 in BWA gave rise to pH in the mixture to values which change the effectiveness of the solution to dissolve P in the material, and which decrease the ability of the method to represent soluble P in BWA. According to studies of Schiemenz *et al.* (2011) the P fertilisation effect of BWA might be as high as that of artificial P fertilisers, and therefore P solubility in citric acid is possibly more applicable to estimate P fertilisation effects of biomass ashes.

10.2 Effect of minNPK on pH

Measurements of soil pH based on samples, which were taken at the last day of the experiment, indicate an acidifying effect of minNPK treatments. Differences in soil pH of the unfertilised control treatment were, however, not significant (Figure 2).

Application of ammonium fertilisers typically lowers soil pH as explained by Chien *et al.* (2008). When NH_4^+ nitrifies into NO_3^- under aerobic conditions, H^+ is an inevitable by-product of the chemical process. Also when plants take up N in the form of NH_4^+ they release H^+ to maintain their inner charge balance. There can be measured increased amounts of hydrogen ions in the rhizosphere of plants after uptake of NH_4^+ (Brady and Weil, 2008). Schroder *et al.* (2011)

assessed long-term use of mineral N fertilisation with regards to soil acidification and found that pH continuously decreased with time and that pH values were significantly related to the amount of mineral N applied.

11 APPENDIX V: REFERENCES

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