This is a post-peer-review, pre-copyedit version of an article published in *Nutrient Cycling in Agroecosystems*. The final authenticated version is available online at: https://doi.org/10.1007/s10705-017-9881-7

Yield, nitrogen recovery efficiency and quality of vegetables grown with organic waste-derived fertilisers

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ABSTRACT

More sustainable production of high-quality, nutritious food is of worldwide interest. Increasing nutrient recycling into food systems is a step in this direction. The objective of the present study was to determine nitrogen (N) fertiliser effects of four waste-derived and organic materials in a cropping sequence of broccoli, potato and lettuce grown at two latitudes (58° and 67° N) in Norway during three years. Effects of anaerobically digested food waste (AD), shrimp shell (SS), algae meal (AM) and sheep manure (SM) at different N application rates (80 and 170 kg N ha^{-1} for broccoli, and 80 and 60 kg N ha^{-1} for potato and lettuce, respectively) and residual effects were tested on crop yield, N uptake, N recovery efficiency (NRE), N balance, N content in produce, mineral N in soil, product quality parameters and content of nitrate in lettuce. Mineral fertiliser (MF) served as control. Effects on yield, N uptake, NRE, N balance and product quality parameters could to a great extent be explained by estimated potentially plant-available N, which ranked in the order of AD>SS>SM>AM. Results for crops fertilised with AD and SS were not significantly different from MF at the same N application rate, while AM, in agreement with its negative effect on N mineralisation, gave negative or near-neutral effects compared to the control. No residual effect was detected after the year of application. The results showed that knowledge about N dynamics of relevant organic waste-derived fertilisers is necessary to decide on the timing and rate of application.

Keyword: organic fertiliser, broccoli, potato, lettuce, nitrogen use efficiency, vegetable quality

INTRODUCTION

In agriculture and horticulture, a major aim is cost-efficient production of sufficient high-quality, nutritious food without health hazards and contaminants and with minimum detrimental impact on the environment. In organic production systems, this is pursued through the design and management of locally adapted agroecosystems in accordance with ecological principles (IFOAM 2014). The cycling and supply of nutrients to support crop growth is essential and often a main focus of farm management practice (Gliessman 2007); the organic farming standards require that operators "shall return nutrients, organic matter and other resources removed from the soil through harvesting by the recycling, regeneration and addition of organic materials and nutrients" (IFOAM 2014). These approaches are also among the solutions suggested to mitigate potassium deficiency in some soils and agricultural systems (Öborn et al. 2005) and to meet the global challenge of increasing phosphorus demand and decreasing rock phosphate availability within a few decades (Cordell et al. 2009). Currently, however, nitrogen (N) is most often the growth-limiting nutrient (Mosier et al. 2004; Zebarth et al. 1995), particularly in organically grown cash crops (Berry et al. 2002). In such systems, which are often on stockless farms, the limitation is partly due to scarcity of traditional resources, such as animal manure, and costs related to setting aside field area for green manure production in combination with too short growing season for both cash crop and manuring crops. Poor N use efficiency (NUE) due to microbial immobilisation and humification and to poor synchrony of fertiliser N mineralisation and nutrient uptake of the crop, can lead to reduced crop yield and also result in N loss to the environment by gas emission or leaching (Huggins and Pan 2003). The applied N taken up by the produce is commonly expressed as N recovery efficiency (NRE, Cassman 2002; Crasswell and Godwin 1984; Fixen 2005; Mosier et al. 2004; Raun and Johnson 1999). As NUE tends to be high when N input rate is low, an important objective is to improve the NUE without reducing the productivity and quality of the produce (Roberts 2008). Additionally, if mineralisation occurs too late in the growing period, undesirably high concentrations of nitrate (NO_3^-) in leafy vegetables may occur. Overall N scarcity and poor synchrony are likely to occur when growing vegetables, e.g., *Brassica* spp., that have high N demands (Nkoa et al. 2003), especially within the arctic circle, where the growing season is short and N mineralisation from soil organic matter may be severely limited by low soil temperatures. This definitely represents a bottleneck to obtaining acceptable yields of sufficient quality (Machado et al. 2010).

Consequently, to increase the current production of organic crops and to meet the anticipated challenges of global food production in a sustainable and economic way, there is a need to investigate the fertiliser value of potential organic nutrient resources. Ideally, local resources should be used, considering the environmental costs of transportation. In Norway, there are from agriculture, aquaculture and household organic wastes or by-products that are relevant as fertilisers. The organic food waste sorted out from household wastes amounted to 180 000 Mg in 2015 (personal communication, Statistics Norway's Information Centre, Oslo, Norway). This material can potentially be utilised as fertiliser either from compost or from by-product of biogas production (RVF-Utveckling 2005). From fish industry, registered amounts of organic waste in 2012 was 816 500 Mg, including wastes from cod and herring offshore fishing, fish farming, shrimp and crab industry (RUBIN 2012). According to RUBIN (2012), 77% of by-products from fish industry are being utilised. Waste from shrimp industry amounts to 4 500 Mg, which gives a utilisation rate of 50%. As the aquaculture industry currently is growing, the potential amount of organic waste from fish is increasing. In addition to the given numbers, there are large unrecorded amounts of nutrients flowing as feed waste and excrements into the areas surrounding aquaculture cages. Seaweeds are relevant for capturing nutrients in fish farms (bioremediation and integrated multi-trophic aquaculture, Reid et al. 2013). Seaweeds can be harvested and utilised for feed, bioethanol fermentation and for energy production by biogas digestion (Roesijadi et al. 2010). Residues from biogas production, as well as the seaweeds itself, can be utilised for agricultural purposes as fertiliser or soil conditioner. To utilise such materials in agriculture, knowledge is needed to design sustainable, integrated bioenergy and nutrient recycling systems (Barrington et al. 2009).

The aim of the present study was to determine the fertiliser value of four locally-sourced organic materials in a cropping sequence of broccoli, potato and lettuce. The fertiliser materials tested were solid sheep manure (SM) from a local farmer, extruded shrimp shell (SS), anaerobically digested food waste from biogas production (AD), and a commercially available algae meal product (AM) originating from *Ascophyllum nodosum*. The effects on crop yield, N uptake, NRE of applied N, N balance and selected crop quality parameters were determined. Relationships between estimated potentially plant-available N and, respectively, yield, N uptake, N content in produce, NRE and selected quality parameters were investigated. Control plots of none fertiliser (NF) and mineral fertiliser (MF) were included.

MATERIALS AND METHODS

Site description, soil properties and weather data. The experimental fields were located at the Norwegian Institute of Bioeconomy Research, Division Bodø (Northern Norway, 67°28'N, 14°45'E) and Division Landvik, Grimstad (Southern Norway, 58°34'N, 8°52'E) during the growing seasons of 2008, 2009 and 2010. Detailed information about soil properties, cropping history and tillage prior to the experiment, and meteorological data are described by Øvsthus et al. (2015). In brief, the field in Bodø was a sandy orthic humo-ferric podzol (Haraldsen 1989), while the field in Grimstad was a gleyed sombric brunisol (Hole and Solbakken 1986) with a southwest-facing slope of 2–4% and 2–6%, respectively. Details about nutritional status of soil are summarised in Table 1. Prior to cropping experiment, the fields were, respectively, managed as organic cattle pasture and organic grass seed ley. From June to September in 2009 in Bodø and Grimstad, respectively, average temperature was 12.2 and 15.2°C, sum rainfall 482 and 474 mm, and sum sunshine hours 762 and 894 h. The corresponding figures in 2010 were 11.0 and 15.0°C, 299 and 351 mm, and 634 and 909 h, respectively.

Design and management of the field experiments

A factorial field experiment with fertiliser materials (AD, SS, SM, AM, MF and NF), nitrogen (N) application rates, and additive fertiliser and crop rotation effects as independent variables, was established in an experiment with a crop rotation of broccoli (first-year crop), potato (second-year crop) and lettuce (third-year crop), as presented in Table 2. Details about nutritional status of fertiliser materials are presented by Øvsthus et al. (2015) and are summarised in Table 3. Each of three blocks was split in three large plots (30 m × 5.6 m and 30 m × 6.4 m in Bodø and Grimstad, respectively), of which one each year served as the starting point of the crop sequence; i.e., broccoli was present on one of the three large plots in each of the three years, potato in two and lettuce in one year. The three large plots were divided into ten sub-plots (6 × 2.8 m and 6 × 3.2 m in Bodø and Grimstad, respectively) for the combinations of fertiliser type, rate and residual effect. The treatments on sub-plots were randomised within each block.

Fertiliser materials were broadcast by hand. Incorporation of fertiliser materials on broccoli plots were done as described by Øvsthus et al. (2015). In 2009, all organic fertiliser was incorporated before planting broccoli and potato. For MF, 50% and 75% of the total amount was supplied prior to planting, and the remaining 50% and 25% was supplied twice and once during the growing season of broccoli and potato, respectively. In 2010, all fertilisers were applied split in the same way as MF, except AM, all of which was incorporated before planting. On broccoli plots, the second and third application took place three and five weeks after planting. On potato plots, the second fertiliser application took place when the haulm reached 0.1 m height. On lettuce plots, all fertilisers were applied before planting. For all crops, fertiliser applied before planting was worked into the soil by rotary harrowing. Fertilisers top-dressed during the growing season were not incorporated. In dry periods, a rotary broadcaster was used for irrigation.

The production of the seedlings of broccoli *(Brassica oleracea* L. var. *italica* **cv**. Marathon*)* are described by Øvsthus et al. (2015). Seedlings of lettuce (*Lactuce sativa L. cultivar 'Ametist'* and *Lactuce sativa L. cultivar 'Argentinas'*) were produced by the same method as seedlings of broccoli by using organic peat-based compost, organic chicken manure and plugtrays. The mother tubers of potato (*Solanum tuberosum L. cv. 'Troll')* were chitted at 15°C for 6 weeks before planting. Broccoli and potato were planted with 18 plants in each row and 4 rows on each sub-plot. The planting distance was

330 mm, the row space was 700 mm, and the tramline spacing was 700 and 800 mm in Bodø and Grimstad, respectively. The lettuce cultivars ‘Ametyst’ and ‘Argentinas’ were planted on biodegradable film (Orlemans plastic B. V., Genderen, The Netherlands) in beds of four and five rows in Grimstad and Bodø, respectively. Each lettuce plot consisted of two beds, and in total there were eight and ten rows per plot in Grimstad and Bodø, respectively. The plant distances within rows were 400 mm, giving in total 120 lettuce plants on each plot in Grimstad and 150 in Bodø. ‘Ametyst’ and ‘Argentinas’ were planted in every other row. Two different cultivars were chosen due to expectations of possible unequal development conditions in different climates. In Grimstad ‘Argentinas’ reached maturity first and was selected as the earliest variety at this location. In Bodø ‘Argentinas’ grew more slowly and was outperformed by ‘Ametyst’, which was selected as the best variety for this location. The results presented are for the cultivar first reaching maturity on each location.

In the first year of the field experiment, broccoli was planted on biodegradable film based on corn starch (BioAgri, BioBag Norge AS, Askim, Norway) with the aim to reduce leaching and prevent weed growth. Due to problems with dissolution and mineralisation of fertilisers in the upper soil layers close to the biofilm, this practice was abandoned in the following years. Moreover, the results for broccoli in 2008 were considered atypical as compared to those in 2009 and 2010. Therefore, results obtained in 2008 were not included in the average values presented.

Monitoring sampling and analysis

To avoid edge effect, the first plant in each row was not sampled, and soil was sampled at a distance larger than 0.33 m from the plot boundary. Soil samples were collected from two soil depths (0–0.3 and 0.3–0.6 m). In the spring prior to producing broccoli the first year, the average soil mineral N content in Bodø and Grimstad, respectively, was 22.8 and 20.1 kg N ha^{-1} in the 0–0.3 m soil layer and 8.5 and 6.1 kg N ha^{-1} in the 0.3–0.6 m layer. Further sampling was done in spring, between tillage and planting, and once after harvest. On each sub-plot, 6–10 soil cores were randomly collected, mixed by hand, and a composite sample from each depth and each sub-plot was stored at –18°C until analysis of inorganic N.

NH_4^+ and NO_3^- were determined at Norwegian Institute of Bioeconomy Research (NIBIO, location Apelsvoll, Kapp, Norway) by extraction of 40 g soil in 200 ml 1 M KCl and analysis by a Flow Injection Analyser (FIAstar 5000, Foss Analytical AB, Sweden).

For broccoli, harvesting criteria and determination of yield, quality and N content are described by Øvsthus et al. (2015)

For potato, height of the haulm was monitored in the beginning of September. Potato haulm and tuber of ten plants on each sub-plot were harvested separately in the end of September and used for analyses. The remaining sub-plots were harvested for determination of total yield. Haulm and tubers were weighed, and tubers were counted and their size recorded before they were milled in a meat grinder and dried at 60°C for determination of dry weight (DW) and Kjeldahl N, as described for broccoli by Øvsthus et al. (2015). Reduced quality (green tuber, hollow heart and crack growth) and percentage tubers smaller than first-class size (< 40 mm) were recorded.

For lettuce, a random selection of 20–30 heads from each sub-plot were harvested when 80% of the plants had reached maturity stage, resulting in three different harvest dates depending on fertiliser treatment. Average weight per lettuce head was determined and the results computed as total yield per hectare without consideration of the number of lettuce plants that died or did not reach maturity, and that some treatments resulted in bigger heads than what is usually considered as harvesting stage. For determination of DW and Kjeldahl-N, 6–10 randomly chosen plants from each sub-plot were homogeneously milled and mixed in a meat grinder, samples of about 20 g were frozen at –18°C and a sub-sample of about 500 g was dried at 60°C and weighed. NO_3^- was determined by extraction of 20 g frozen sample in 100 ml boiling water, and analysis by spectrophotometry using a FIAstar 5000 Analyzer (Foss Analytical AB, Sweden). Quality parameters and size class were recorded according to NS 2830.

Apparent N recovery efficiency and N balance

Apparent nitrogen recovery efficiency (NRE) of the fertilisers was calculated as given by Crasswell and Godwin (1984).

$$NRE = (U–U_0)/N_A \quad \text{(Equation 1)}$$

where U and U_0 are uptake of N (kg ha^{-1}) in aboveground plant biomass (including content of N in potato tubers) with and without fertiliser, respectively, and N_A is the amount of N applied (kg ha^{-1}).

N balance (NB) is the difference between accumulated input and output after one, two and three years, respectively.

$$NB = N_A – N_Y \quad \text{(Equation 2)}$$

where N_Y is the amount of N in yield (kg ha^{-1}) removed from field. The calculations of NRE and NB assume equal mineralisation of soil N on all plots.

Statistical analysis

Analysis of variance (ANOVA) by general linear model (GLM) in Minitab 17 (Minitab Inc, State College, PA, USA) was performed for yield, N and quality variables. For each location separately, we used a model with fertiliser treatment as a fixed factor, while year, interaction between fertiliser treatment and year, and replication nested within year was used as random factors. To enable the use of Tukey’s multiple comparison test on treatment differences (P = 0.05) in Minitab, all factors were considered fixed.

Regression analysis was performed in Minitab 17 of yield, N and quality variables on potentially plant-available N from fertiliser materials during the growing season as estimated by Øvsthus et al. (2015) from results obtained by Øvsthus et al. (manuscript in preparation) during incubation of the fertilisers in soil at controlled temperature and moisture.

RESULTS

Yield responses

All crops yielded well with shrimp shell (SS), anaerobically digested food waste (AD) and mineral fertiliser (MF) (Tables 4 A and B). With algae meal (AM), however, the yields and N uptake tended to be smaller than with no fertiliser (NF), but the difference was not statistically significant. The yields with sheep manure (SM) were intermediate.

Broccoli yield has previously been presented by Øvsthus et al. (2015). In brief, on the average across two years and two locations, application of 170 kg N ha^{-1} as MF, AD, SS and SM resulted in, respectively, 106, 68, 55 and 32% larger yield than with NF, whereas AM fertilisation gave 53% smaller yield. Yields after AD and MF fertilisation (170 kg N ha^{-1}) were not significantly different across year and location (data not shown). A similar yield pattern was observed for broccoli fertilised with 80 kg N ha^{-1}, but the differences between treatments were smaller.

Potato and lettuce fertilised with 80 and 60 kg N ha^{-1}, respectively, showed a similar yield pattern as for broccoli (Tables 4 A and B). Fertilisation with MF, AD and SS, respectively, resulted on the average across two years and two locations in 55, 31, and 42% larger potato yield than NF. The corresponding figures for lettuce were 76, 34 and 43%. Yields obtained with SS and MF fertilisation for potato (80 kg N ha^{-1}) and lettuce (60 kg N ha^{-1}) were not significantly different across year and location (data not shown).

Yields of broccoli, potato and lettuce were linearly correlated to our estimated amount of potentially plant-available N from the fertilisers during the growing season of the test crops (results not shown in figures or tables). Regression analysis conducted over year and location resulted in R^2 values of 50.5, 14.2 and 48.6 ($p<0.001$), respectively, for broccoli, potato and lettuce. Year and location effects occurred for yields of broccoli and potato in 2009 and 2010.

Size, quality and marketable yield

Generally, the broccoli quality was marketable, with first class quality as described in NS2823:1999, except some occurrence of uneven maturity of buds within heads, heads with buds that did not mature and some small heads (below 60 mm diameter). Broccoli fertilised with AM had a high percentage that did not meet first-class size requirement and a high percentage of heads not harvested. Broccoli fertilised with MF, AD and SS at high N level (170 kg N ha^{-1}) tended to have a larger proportion of broccoli >100 mm (Figure 1).

Potato size distribution tended to be the same with all fertilisers except for AM, which had a higher proportion of larger-sized tubers (Figure 1). This result was found both in the year when AM was applied at a rate of 80 kg N ha^{-1} and when the residual effect of previous AM application was determined. In the growing season, the tallest potato haulm was observed with MF, AD and SS (Tables 4 A and B). The percentage tubers with physical damage was highest with AM fertilisation, however, the difference was only significant when GLM analysis was conducted for results across both years and locations.

Lettuce treated with MF, SS and AD had clearly larger heads than lettuce fertilised with AM and NF (Figure 1), resulting in a large proportion of heads meeting the first-class size limit of 350 g. With AM, more than 90 % of the total yield did not meet the first-class quality standards. Lettuce fertilised with MF obtained higher NO_3^- content than with the other fertilisers at 60 kg N ha^{-1}, but it was not significantly different from that of AD-fertilised lettuce. The content of NO_3^- in lettuce ranged on the average across locations in year 2010 from 6.1 to 157.3 mg kg^{-1} fresh weight (AD1 Grimstad and MF Bodø, respectively; data not shown).

N uptake, N content and N balance

For all crops, total N uptake was smallest on NF and AM plots, and largest in MF-fertilised broccoli and lettuce (Tables 5 A and B). For potato, the N uptake was similar for MF, AD and SS. The average N uptake values across year and location were in the range of 63.5–165.1, 40.8–96.3, and 20.6–65.7 kg N ha^{-1} in broccoli, potato and lettuce, respectively. For all crops in both years and on both locations, the N uptake was positively correlated with estimated potentially plant-available N from the organic fertiliser materials (Figure 2).

The treatment effects on plant N content were small (Tables 5 A and B). The average values across year and location were in the range of 16–33, 11–12 and 13–32 g kg^{-1} in broccoli, potato and lettuce, respectively. In broccoli and lettuce, the N contents were highest with MF and AD. The results for potato, however, did not show a similar pattern.

The N balance of the 3-year cropping sequence was positive for all treatments except for NF (Tables 5 A and B). The ranking of N balance of the treatments in increasing order was NF<MF<AD<SS<SM<AM.

Apparent N recovery efficiency

NRE was affected by fertiliser treatment (Figure 3), and on the average across year and location the values ranged from –9 to 57, –13 to 56 and –20 to 65% for broccoli, potato and lettuce, respectively. AM resulted in negative NRE, which was positively correlated with potentially plant-available N (R^2=35.5, 55.6 and 40.7 for broccoli, potato and lettuce, respectively; P=0,000). In all crops, highest NRE was found with MF fertilisation, but it was not significantly higher than NRE obtained by SS2 (shrimp shell at 170 kg N ha^{-1}) and AD1 (anaerobically digested food waste at 80 kg N ha^{-1}) in broccoli, and SS1 (shrimp shell at 80 kg N ha^{-1}) and AD1 in potato. NRE obtained with SM (sheep manure) was intermediate.

Mineral N in soil and residual effects

After the harvest of broccoli in autumn, there were differences in content of inorganic N in plots at the upper N level of AD (AD2) compared to plots fertilised with other organic materials. The difference was found both in the upper and lower soil layers. The difference was not significantly different form

MF-fertilised plots. Contents of inorganic N in soil after growing potato or lettuce were not affected by fertiliser treatments. The residual effect of fertilisation in previous years on yield of unfertilised potato and lettuce was small or undetectable. The content of inorganic N in soil in spring was not significantly influenced by the fertilisation treatments in previous years (data not shown).

DISCUSSION

There were positive linear relationships between yield, N uptake, NRE or tested quality parameters, and the estimated potentially plant-available N from the fertiliser materials, which was inversely correlated with C:N ratio of the different materials (Øvsthus et. al, manuscript in preparation). This is in agreement with a normally strong yield-limiting effect of sub-optimal N availability (Cassman 2002; Zebarth et al. 1995), as typically found in organic agriculture (Berry et al. 2002), and with the relatively high negative correlation usually found between N mineralisation and the C:N ratio of organic materials (e.g., Nicolardot et al. 2001). Yield, N uptake and NRE depend on a complex range of factors including those affecting N mineralisation, N losses and crop N demand (Mosier et al. 2004). Therefore, deviations from linear relationships and for deviant single observations are to be expected.

The results for AM, i.e., the lowest yield, N uptake and NRE and the highest N balance values, were remarkable to the extent that this dried and milled seaweed product is being marketed as fertiliser and soil conditioner (http://www.algea.com/index.php/algeafert-meal). However, the results were expected considering its relatively high C:N ratio (C:N=37) and net immobilisation detected in the incubation experiment by Øvsthus et. al. (manuscript in preparation) and are in accordance with results of other studies on materials with similar decomposability and C:N ratios (Breland 1996; Jensen et al. 1999; Vigil and Kissel 1991). Breland (1996) found that ryegrass with a C:N ratio of 26–50 (depending on plant part and N fertilisation), in incubation tended to cause a small temporary net N immobilisation and a tendency of only a very limited re-mineralisation during a time period comparable to the present experiment. In the present experiment with AM, there was neither higher concentration of NO_3^- in soil in autumn or subsequent spring nor larger yield recorded as residual effect of AM fertilisation. This is consistent with the finding of Breland (1996b) that a ryegrass crop ploughed into soil in late autumn had a close to neutral residual effect on subsequent spring grain. Nevertheless, a positive effect on soil N mineralisation may be expected after several years of AM application due to accumulated immobilisation of N, the size of which eventually will become large enough to contribute significantly to crop N supply by its re-mineralisation, in spite of small contributions from each single-year cohort. For example, in a crop rotation experiment, Breland and Eltun (1999) observed increased C and N mineralisation rates for an extended period of incubation (449 days at 15°C) in soil that for only five years had received more organic matter as perennial root growth, plant residues and animal manure, as compared to an all-arable cropping sequence without animal manure. Their results could be modelled as mainly an increase in two conceptual pools of soil organic matter with carbon half-lives at 15°C of 0.76 and 12.7 years, respectively. Consequently, the present results, in agreement with previous ones (Asdal and Breland 2003; Breland 1996; Breland 1996b; Jensen et al. 1999; Vigil and Kissel 1991), suggest that when there is a need for a relatively rapid and predictable N supply for N-demanding crops such as broccoli, materials with a high concentration of inorganic N such as AD, or a rapidly net N mineralising material such as SS should be used. The short-term effects of SM in the present experiment were intermediate, most likely due to relatively stable C compounds (Asdal and Breland 2003). A low C:N ratio and a high concentration of inorganic N at the time of application for materials such as AD and SS could be combined with materials of higher C:N ratio, such as AM, in order to build up a more stable long-term soil N mineralisation capacity and to reduce the likelihood of ammonia volatilisation, nitrous oxide emission and nitrate leaching shortly after application.

Little is still known about decomposition and N mineralisation from algae. However, it seems likely that species with lower C:N ratio than the current AM will give a more positive short-term net N mineralisation (Jensen et al. 2005; Nicolardot et al. 2001) and, consequently, fertiliser effect on N-demanding crops.

In addition to neutral or negative net N mineralisation from AM, other factors might have contributed to its poor effects on crop yields. AM has a total S content five times higher than that of MF. However, plants are generally not sensitive to high S level in soils (Mengel and Kirkby 2001). Salt concentration in the fertilisers was not measured, but NaCl in seaweeds may have influenced yield. Typical Na^{+} and Cl^{-} toxicity symptoms were not seen, although yellowish leaves were observed. However, these symptoms could equally well have been caused by deficiency of N, as suggested by the negative net N mineralisation from AM (data not shown). As both lettuce and potato are sensitive to Cl^{-} toxicity, further research is needed to determine whether NaCl concentrations in seaweed products are sufficiently low to avoid toxic effects on plant growth.

SS and AD had fertiliser effects that did not differ significantly from those of MF. The NRE for all MF-treated crops were more than 50%, which is similar to results for broccoli reported by Zebarth et al. (1995), but lower than found by Vågen (2005). Quality of fertiliser material, timing and amount of plant-available N, the type of mineral N (NH_4^{+} or NO_3^{-}), N immobilisation, ammonia volatilisation, nitrous oxide emission and nitrate leaching may potentially explain some of the gap between applied N and apparent N recovery in crops (Cameron et al. 2013; Galloway et al. 2003; Raun and Johnson 1999). In addition to the yield and N data, the crop quality indices measured in the field experiments (discarded product, damages (physical or disease), per cent harvested, N content, height of potato haulm, size distribution) also suggested that the effects of AD and SS were similar to those of MF. The high proportion of damage and discarding by AM fertilisation is in accordance with other fertiliser experiments that have included treatments that gave similar N availability (Doltra et al. 2011).

The higher NO_3^{-} concentration in lettuce fertilised with MF compared to other treatments could be explained by the amount, availability of N and form of mineral N at application, which is found in other experiments as well (Anjana et al. 2007; Chena et al. 2004; Santamaria et al. 2001;). Due to reduced N availability, vegetables fertilised with organic materials often are lower in NO_3^{-} concentration than vegetables having received inorganic fertiliser at similar N rates (Raupp 1996). If N is present as NH_4^{+}, as in AD and SM, the level of NO_3^{-} in vegetables has been found to be lower than when N is in the form of NO_3^- (Santamaria et al. 2001), which can accumulate in crops and be stored in the vacuole. In the current experiment, the fertilisers were supplied prior to planting and the total N supply was small, and all NO_3^- concentrations were low compared to studies performed by Santamaria (2006).

CONCLUSIONS

1) Fertiliser effects on yield, N uptake, NRE, N balance and quality parameters of vegetable crops were to a large extent explained by the potential amount of inorganic N becoming available during the growing season, as estimated on the basis of results obtained by Øvsthus et. al. (manuscript in preparation) during incubation of the fertilisers in soil at controlled temperature and moisture. Consequently, such a test seems essential for selecting alternative fertilisers, deciding on application rates and predicting effects on crop yield and quality.

2) The materials with the most inorganic N at application or large net N mineralisation had fertiliser effects similar to those of mineral fertiliser, showing a potential for turning waste or unutilised materials into resources with the potential for replacing mineral N fertilisers.

3) No residual effect was detected in the year after application, but the materials with weaker or no fertiliser effect and less or no net N mineralisation may, if used repeatedly, be expected to contribute to the more long-term capacity of soil to provide plant-available N.

4) To supply adequate fertiliser for N-demanding crops in the short term while also increasing the more long-term N-supplying capacity of the soil, it seems desirable to combine the use of waste or alternative fertiliser materials that release plant-available N rapidly with materials retaining or causing immobilisation of N. To judge whether such materials should be mixed or kept separate in time or space requires further investigation.

ACKNOWLEDGMENT

We are grateful to the Research Council of Norway, the counties of Nordland and Troms, and the Norwegian Institute of Bioeconomy Research for financial support of this work.

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Table 1. Chemical properties and texture of the upper 0.3 m soil layer of the experimental fields in Bodø and Grimstad (samples taken in spring 2008).

	Chemical properties						**Texture**		
Location	pH*	TC** (g kg^{-1})	TN*** (g kg^{-1})	$N0_3^-$-N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	TP**** (mg kg^{-1})	Sand	Silt	Clay
Bodø	6.1	21	1.7	7.0	3.9	840	91	7	2
Grimstad	5.9	30	1.6	11.1	1.2	790	87	10	3

* pH in water
**TC = total carbon
***TN = total nitrogen
****TP = total phosphorus

Table 2. Cropping system, type of fertiliser and application amounts (kg N ha^{-1}) for the ten different treatment combinations in field trials. Abbreviation used for fertiliser codes are AD = anaerobically digested food waste; SS = extruded shrimp shell; SM = sheep manure; AM = algae meal; NF = no fertiliser applied; MF= mineral fertiliser.

Treatment combination codes	Fertiliser codes	1st year crop: broccoli	2nd year crop: potato	3rd year crop: lettuce
		N, kg ha^{-1}	N, kg ha^{-1}	N, kg ha^{-1}
AD1	AD	80	80	0
AD2	AD	170	0	60
SS1	SS	80	80	0
SS2	SS	170	0	60
SM1	SM	80	80	0
SM2	SM	170	0	60
AM1	AM	80	80	0
AM2	AM	170	0	60
MF	MF	170	80	60
NF	NF	0	0	0

Table 3. Chemical and physical properties of anaerobically digested food waste (AD), extruded shrimp shell (SS), sheep manure (SM) and algae meal (AM).

					Chemical properties							Physical properties
Fertiliser codes	pH*	DM %	TOC (g kg^{-1} DM)	TKN (g kg^{-1} DM)	NH_4^+-N (g kg^{-1} DM)	$N0_3^{-}$-N (g kg^{-1} DM)	C:N ratio	PPAN (%)**	P (g kg^{-1} DM)	K (g kg^{-1} DM)	S (g kg^{-1} DM)	
AD	8.6	1.3	307	254	153	0	1.2	86.3	18	106	8	liquid part
SS	9.2	90.2	301	72	0	0	4.2	54.1	27	1	4	dried and pelleted
SM	8.8	19.4	396	37	13	0	17.4	53.9	9	22	5	solid part, containing traces of straw
AM	6.0	89.1	406	11	0	0	36.9	-24.5	1	16	26	dried and crushed seaweed, mainly *Ascophyllum nodolus*

* pH in water
**PPAN= Potentially plant-available N during the growing season as estimated by Øvsthus et al. (2015) from results obtained by Øvsthus et. al. (manuscript in preparation) during incubation of the fertilisers in soil at controlled temperature and moisture.

Table 4A. Yield and selected quality parameters* on the Grimstad site for broccoli, potato and lettuce in a 3-year cropping sequence with anaerobically digested food waste (AD), shrimp shell (SS), sheep manure (SM) and algae meal (AM) as fertilisers at two N application rates (1 and 2), mineral fertiliser (MF) and no fertiliser (NF). For detailed explanation of treatments and measured parameters, see the text and Table 2). For broccoli and potato, results are means of data from 2009 and 2010, and for lettuce, results are from 2010 only. Different letters within a column denote statistically significant difference at P<0.05 according to Tukey's range test, and the p-values pertain to effects of treatment (T), year (Y) and replication nested within year [Replication(Y)] as determined in ANOVA.

	Broccoli				Potato					Lettuce		
Treatment Code**	Total yield (kg ha^{-1})	Mean head wt. (g pl^{-1})	Size-discarded (% < 60 mm)	Head harvested (% of planted)	Total yield (kg ha^{-1})	Mean tuber wt. (kg pl^{-1})	Physical damage (%)	Size-discarded (% < 40 mm)	Mean haulm ht. (mm)	Total yield (kg ha^{-1})	Mean head wt. (g pl^{-1})	Discarded (%)
AD2	11338^{ab}	341.0^{ab}	0^{b}	86.7^{a}	16116^{c}	0.4255^{c}	10.6^{ab}	24.3	576.1^{c}	34966^{abcd}	559.5^{abcd}	0
SS2	9612^{bc}	315.2^{ab}	0.5^{b}	83.2^{ab}	16869^{c}	0.4453^{c}	7.6^{ab}	18.7	583.0^{c}	35946^{abc}	575.1^{abc}	0
SM2	9511^{bc}	285.3^{bc}	0^{b}	86.8^{a}	20047^{bc}	0.5292^{bc}	3.1^{b}	17.0	623.1^{bc}	37648^{ab}	602.4^{ab}	0
AM2	3267^{e}	159.5^{e}	7.2^{ab}	50.5^{c}	20728^{abc}	0.5472^{abc}	11.7^{ab}	14.0	644.0^{bc}	20512^{e}	328.2^{e}	33.4
AD1	9471^{bc}	267.0^{bc}	0^{b}	92.0^{a}	20802^{abc}	0.5492^{abc}	3.0^{b}	25.6	707.6^{ab}	25817de	413.1^{de}	22.2
SS1	8899^{bc}	253.1^{bcd}	0.3^{b}	92.2^{a}	22956^{ab}	0.6061^{ab}	8.1^{ab}	15.8	690.2^{b}	27792^{bcde}	444.7^{bcde}	21.1
SM1	9456^{bc}	286.4^{bc}	3.2^{ab}	91.3^{a}	20589^{abc}	0.5435^{abc}	4.9^{b}	20.3	689.1^{b}	33104^{abcd}	529.7^{abcd}	2.5
AM1	4641de	165.9^{de}	13.0^{a}	67.3^{bc}	17075^{c}	0.4508^{c}	21.3^{a}	17.0	627.0^{bc}	35458^{abcd}	567.3^{abcd}	5.8
MF	13915^{a}	379.0^{a}	0^{b}	94.0^{a}	25843^{a}	0.6823^{a}	3.6^{b}	16.2	807.1^{a}	40878^{a}	654.1^{a}	0
NF	7267^{cd}	208.1^{cde}	0.3^{b}	91.3^{a}	15774^{c}	0.4164^{c}	10.4^{ab}	20.2	559.0^{c}	27436^{cde}	439.0^{cde}	27.4
Mean values across treatments within year												
2009	10188^{a}	281.9^{a}	3.6	91.8^{a}	18775^{b}	0.4957^{b}	4.62^{b}	17.7	660.2			
2010	7288^{b}	250.2^{b}	1.3	75.3^{b}	20585^{a}	0.5435^{a}	12.20^{a}	20.2	641.1	31956	511.3	11.2
P-values from ANOVA												
T	0.000	0.000	0.008	0.000	0.000	0.000	0.008	NS	0.000	0.000	0.000	NS
Y	0.000	0.012	NS	0.000	0.018	0.18	0.001	NS	NS			
T*Y	NS	NS	NS	0.006	0.032	0.032	NS	NS	NS			
Replication(Y)	NS	NS	0.049	NS	0.009	0.009	0.011	0.000	0.004	0.026	0.026	0.042

* Total fresh weight yield, mean fresh weight (wt.) per plant (head or tuber), % discarded due to incorrect size (including quality disorder for lettuce), broccoli head harvested (% of planted), tubers with physical damage (% of total yield with errors due to green tuber, hollow heart and crack growth) and average potato haulm height (ht.)

** Treatment codes according to Table 2.

Table 4B. Yield and selected quality parameters* on the Bodø site for broccoli, potato and lettuce in a 3-year cropping sequence with anaerobically digested food waste (AD), shrimp shell (SS), sheep manure (SM) and algae meal (AM) as fertilisers at two N application rates (1 and 2), mineral fertiliser (MF) and no fertiliser (NF). For detailed explanation of treatments and measured parameters, see the text and Table 2. For broccoli and potato, results are means of data from 2009 and 2010, and for lettuce, results are from 2010 only. Different letters within a column denote statistically significant difference at P<0.05 according to Tukey's range test, and the p-values pertain to effects of treatment (T), year (Y) and replication nested within year [Replication(Y)] as determined in ANOVA.

	Broccoli				**Potato**					**Lettuce**			
Treatment Code*	Total yield (kg ha^{-1})	Mean head wt. (g pl^{-1})	Size-discarded (% ≤ 60 mm)	Head harvested (% of planted)	Total yield (kg ha^{-1})	Mean tuber wt. (kg pl^{-1})	Physical damage (%)**	Size-discarded (% <40 mm)	Mean haulm ht. (mm)	Total yield (kg ha^{-1})	Mean head wt. (kg pl^{-1})	Size-discarded (% < 350 g)	Discarded (%)
AD2	8337^{ab}	243.9^{ab}	1.0^{a}	78.2^{ab}	31974^{bcde}	0.7386^{bcde}	6.41^{ab}	18.89^{a}	546.6^{c}	47820^{bc}	0.5356^{bc}	12.92^{bc}	5.4^{ab}
SS2	8585^{ab}	223.8^{ab}	6.2^{a}	86.5^{a}	30181^{cde}	0.6972^{cde}	9.84^{ab}	19.52^{a}	520.8^{cd}	52363^{ab}	0.5865^{ab}	4.79^{c}	2.6^{a}
SM2	6013^{bc}	182.3^{bcd}	5.5^{a}	77.2^{ab}	26551^{e}	0.6133^{e}	8.94^{ab}	15.01^{ab}	491.0^{cde}	36436^{bcd}	0.4081^{bcd}	42.41^{abc}	26.9^{abc}
AM2	2192^{d}	90.2^{e}	12.7^{a}	54.7^{c}	27940de	0.6454d^{e}	4.74^{ab}	12.88^{ab}	452.4^{de}	28242^{d}	0.3163d	68.31^{a}	100.0^{d}
AD1	7889^{ab}	215.8^{abc}	10.5^{a}	84.7^{a}	36224^{abc}	0.8368^{abc}	2.20^{b}	19.16^{a}	640.0^{ab}	38392^{bcd}	0.4300^{bcd}	31.35^{abc}	31.3^{abc}
SS1	6548^{bc}	192.4^{bcd}	4.3^{a}	78.8^{ab}	39049^{ab}	0.9020^{ab}	6.87^{ab}	17.60^{ab}	655.0^{a}	39422^{bcd}	0.4415^{bcd}	36.71^{abc}	36.7^{abc}
SM1	4797^{cd}	152.2^{cde}	8.5^{a}	73.0^{abc}	34533^{bcd}	0.7977^{bcd}	8.79^{ab}	14.02^{ab}	556.5^{bc}	32589^{cd}	0.3650^{cd}	47.61^{ab}	47.6^{bc}
AM1	3018^{d}	102.2^{e}	12.7^{a}	64.8^{bc}	27040^{e}	0.6246^{e}	17.76^{a}	7.65^{b}	421.2^{e}	44614^{bcd}	0.4997^{bcd}	30.42^{abc}	30.4^{abc}
MF	10225^{a}	284.8^{a}	0.8^{a}	83.2^{ab}	41646^{a}	0.9620^{a}	5.73^{ab}	16.22^{ab}	660.1^{a}	67821^{a}	0.7596^{a}	0.00^{c}	0^{a}
NF	4481^{cd}	132.1^{de}	11.3^{a}	78.3^{ab}	27918^{b}	0.6449^{b}	15.07^{ab}	18.40^{a}	493.9^{cde}	34467^{bcd}	0.3860^{bcd}	50.05^{ab}	50.0^{c}
Mean values across treatments within year													
2009	7075.8^{a}	186.1	10.0^{a}	85.3^{a}	40042^{a}	0.9250^{a}	10.84^{a}	8.61^{b}	627.8^{a}				
2010	5342.0^{b}	177.9	4.7^{b}	66.5^{b}	24570^{b}	0.5676^{b}	6.43b	23.26^{a}	459.7^{b}	42217	0.4728	32.46	33.1
P-values from ANOVA													
T	0.000	0.000	0.035	0.000	0.000	0.000	0.018	0.017	0.000	0.000	0.000	0.000	0.000
Y	0.000	NS	0.006	0.000	0.000	0.000	0.021	0.000	0.000				
T*Y	NS	NS	NS	NS	0.001	0.001	NS	NS	0.003				
Replication(Y)	0.001	0.018	0.006	0.010	NS	NS	0.000	NS	NS	0.000	0.000	0.001	0.004

* Total fresh weight yield, mean fresh weight (wt.) per plant (head or tuber), % discarded due to incorrect size (including quality disorder for lettuce), broccoli head harvested (% of planted), tubers with physical damage (% of total yield with errors due to green tuber, hollow heart and crack growth) and average potato haulm height (ht.)
** Treatment codes according to Table 2.

Table 5A. Nitrogen content, total N uptake, harvested N and N balance (accumulated N input and output in the cropping system) on the Grimstad site for broccoli, potato and lettuce in a 3-year cropping sequence with anaerobically digested food waste (AD), shrimp shell (SS), sheep manure (SM) and algae meal (AM) as fertilisers at two N application rates (1 and 2), mineral fertiliser (MF) and no fertiliser (NF). For detailed explanation of treatments and measured parameters, see the text and Table 2. For broccoli and potato, results are means of data from 2009 and 2010, and for lettuce, results are from 2010 only. Different letters within a column denote statistically significant difference at P<0.05 according to Tukey's range test, and the p-values pertain to effects of treatment (T), year (Y) and replication nested within year [Replication(Y)] as determined in ANOVA.

	Broccoli				**Potato**				**Lettuce**		
Treatment code	N content (g kg^{-1})	Total N uptake (kg N ha^{-1})	N in harvested part (kg N ha^{-1})	N balance (kg N ha^{-1})	N content (g kg^{-1})**	Total N uptake (kg N ha^{-1})**	N in harvested part (kg N ha^{-1})	N balance (kg N ha^{-1})	N content (g kg^{-1})	N in harvested part (kg N ha^{-1})	N balance (kg N ha^{-1})
AD2	26.4^{a}	139.9^{ab}	72.6^{ab}	97.4	11.5^{ab}	50.1^{bc}	29.9^{c}	67.5	19.7^{ab}	31.8^{ab}	95.7
SS2	23.8^{abd}	145.2^{ab}	64.8^{abc}	105.2	11.3^{ab}	48.8^{bc}	32.0^{c}	73.2	18.2^{bcd}	32.2^{ab}	101.0
SM2	21.4^{bc}	115.9^{bc}	56.2^{bcd}	113.8	11.3^{ab}	62.7^{bc}	37.1^{bc}	76.7	18.8^{abc}	32.1^{ab}	104.6
AM2	15.8^{d}	70.5^{d}	28.8^{e}	141.2	10.1^{b}	46.6^{bc}	37.5^{bc}	103.7	13.4^{e}	13.3^{c}	150.4
AD1	22.0^{bc}	109.2^{bc}	52.0^{cd}	28.0	11.6^{ab}	64.4^{bc}	45.0^{ab}	63.0	13.6^{de}	20.4^{bc}	42.6
SS1	20.9^{c}	113.3^{bc}	50.6^{cd}	29.4	11.5^{ab}	73.2^{ab}	46.3^{ab}	63.1	14.3^{cde}	23.1^{bc}	40.0
SM1	22.1^{bc}	112.1^{bc}	54.7^{cd}	25.3	12.4^{ab}	69.6^{ab}	41.9^{b}	63.4	14.1^{de}	24.9^{bc}	38.5
AM1	16.1^{d}	69.0^{d}	28.5^{e}	51.5	12.9^{a}	40.4^{c}	31.3^{c}	100.2	14.3^{cde}	26.4^{b}	73.8
MF	25.4^{ab}	174.4^{a}	79.9^{a}	91.1	12.6^{ab}	92.6^{a}	54.0^{a}	117.1	23.1^{a}	42.0^{a}	135.1
NF	19.8^{cd}	82.0^{cd}	40.6^{de}	–40.6	10.9^{ab}	50.5^{bc}	30.3^{c}	-70.9	14.5^{cde}	22.9^{bc}	–93.8

Mean values across treatments within year

2009	25.8^{a}	133.3^{a}	65.5^{a}		ND	ND	41.1^{a}		ND	ND	
2010	17.0^{b}	93.0^{b}	40.2^{b}		11.6	59.9	35.9^{b}		16.4	26.9	

P-values from ANOVA

T	0.000	0.000	0.000		0.043	0.000	0.000		0.000	0.000	

Y	0.000	0.000	0.000				0.000				
T*Y	NS	NS	NS				0.004				
Replication(Y)	NS	NS	NS		0.034	0.000	0.000		NS	NS	

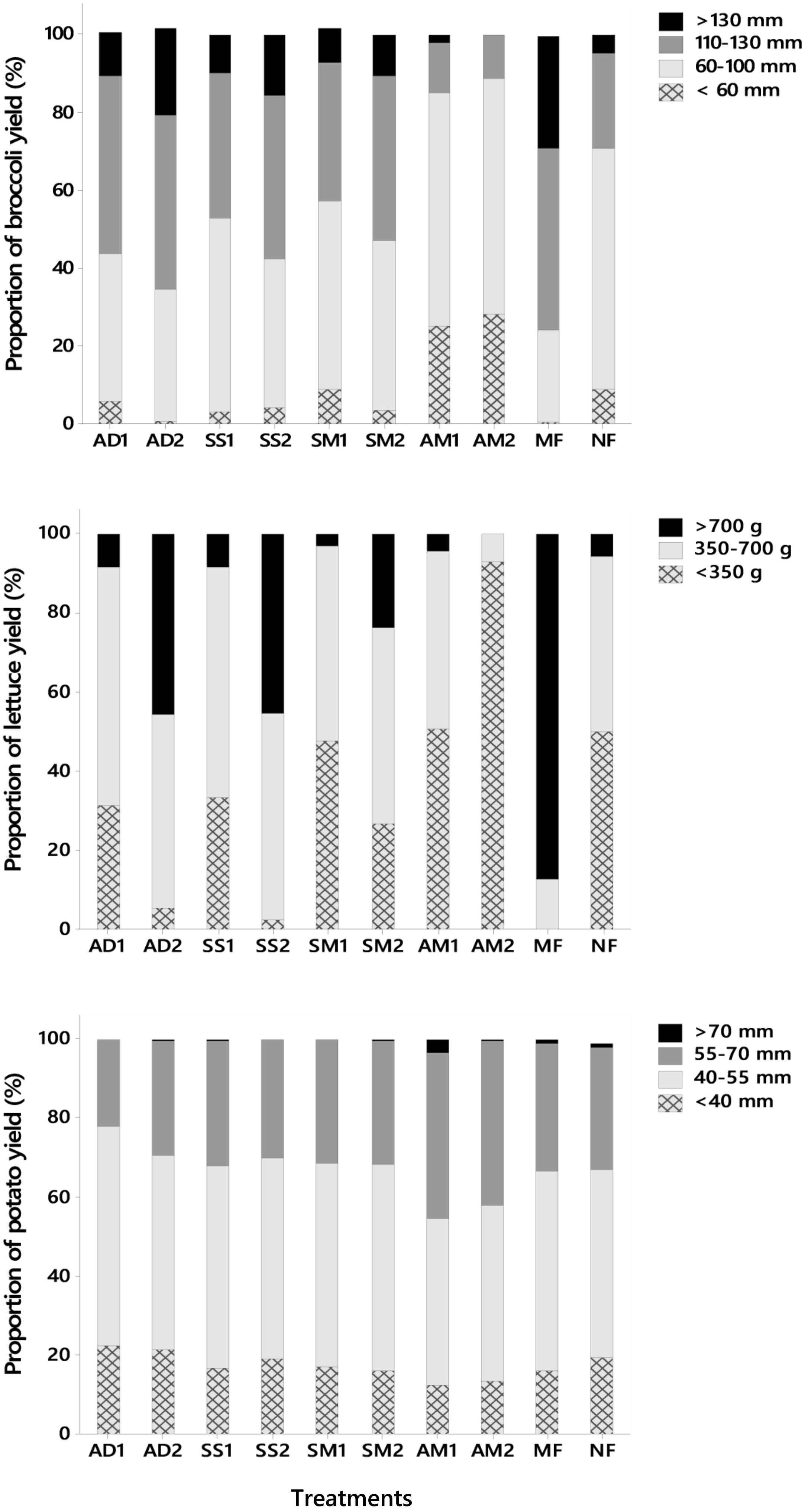
* Treatment codes according to Table 2.
** Results from year 2010 only

Table 5B. Nitrogen content, total N uptake, harvested N and N balance (accumulated N input and output in the cropping system) on the Bodø site for broccoli, potato and lettuce in a 3-year cropping sequence with anaerobically digested food waste (AD), shrimp shell (SS), sheep manure (SM) and algae meal (AM) as fertilisers at two N application rates (1 and 2), mineral fertiliser (MF) and no fertiliser (NF). For detailed explanation of treatments and measured parameters, see the text and Table 2. For broccoli and potato, results are means of data from 2009 and 2010, and for lettuce, results are from 2010 only. Different letters within a column denote statistically significant difference at P<0.05 according to Tukey's range test, and the p-values pertain to effects of treatment (T), year (Y) and replication nested within year [Replication(Y)] as determined in ANOVA.

	Broccoli				**Potato**				**Lettuce**		
Treatment code	N content (g kg^{-1})	Total N uptake (kg N ha^{-1})	N in harvested part (kg N ha^{-1})	N balance (kg N ha^{-1})	N content (g kg^{-1})	Total N uptake (kg N ha^{-1})	N in harvested part (kg N ha^{-1})	N balance (kg N ha^{-1})	N content (g kg^{1})	N in harvested part (kg N ha^{-1})	N balance (kg N ha^{-1})
AD2	32.6^{a}	133.9^{ab}	51.7^{ab}	118.3	10.7^{a}	89.11^{bc}	64.0^{bc}	54,3	29.0^{ab}	57.0^{ab}	57.3
SS2	29.5^{ab}	131.0^{abc}	44.7^{abc}	125.3	10.9^{a}	83.16^{c}	60.1^{c}	65.2	26.7^{bc}	59.8^{ab}	65.4
SM2	26.1^{bc}	97.1^{cde}	36.7^{bcd}	133.3	10.5^{a}	71.81^{c}	50.4^{c}	82.9	23.8^{c}	42.4^{bc}	100.5
AM2	18.2^{d}	56.5^{f}	18.8^{e}	151.2	11.5^{a}	78.21^{c}	57.0^{c}	94.2	25.0^{bc}	24.7^{c}	129.5
AD1	28.4^{ab}	111.8^{bcd}	42.2^{abcd}	37.8	12.3^{a}	119.19^{ab}	85.7^{ab}	32.1	26.9^{abc}	51.7^{abc}	–19.6
SS1	27.8^{ab}	110.8^{bcd}	39.3^{abcd}	40.7	11.4^{a}	117.12^{ab}	84.3^{ab}	54.5	26.2^{bc}	51.9^{abc}	2.6
SM1	24.9^{bc}	84.0^{def}	30.5^{cde}	49.5	10.6^{a}	91.99^{bc}	66.2^{bc}	63.3	26.0^{bc}	44.2^{bc}	19.1
AM1	22.2^{cd}	70.3^{ef}	20.4^{e}	59.6	12.1^{a}	66.22^{c}	48.1^{c}	91.5	26.0^{bc}	54.1^{ab}	37.4
MF	32.8^{a}	155.7^{a}	54.7^{a}	115.3	12.2^{a}	127.78^{a}	94.4^{a}	100.9	31.5^{a}	78.9^{a}	82.0
NF	24.9^{bc}	73.4^{ef}	27.0d^{e}	–27.0	10.7^{a}	79.51^{c}	57.0^{c}	–84	26.3^{bc}	45.5^{bc}	–129.5
					Mean values across treatments within year						
2009	24.8^{b}	130.0^{a}	44.0^{a}		11.6^{a}	116.44^{a}	79.8^{a}				
2010	28.7^{a}	74.9^{b}	29.2^{b}		10.9^{b}	68.38^{b}	53.6^{b}		26.7	51.0	

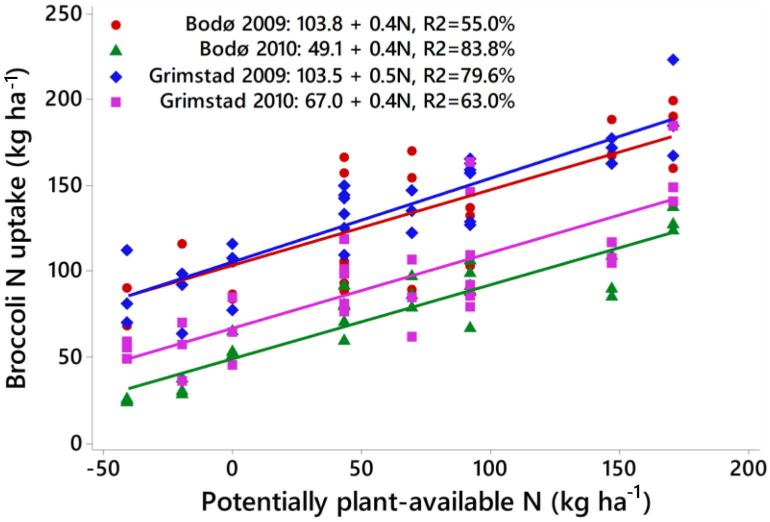
					P-values from ANOVA						
T	0.000	0.000	0.000			0.003	0.000	0.000			0.001	0.001
Y	0.000	0.000	0.000			0.005	0.000	0.000				
T*Y	NS	NS	NS			0.019	NS	NS				
Replication(Y)	0.044	NS	0.001			0.044	NS	NS			NS	0.004

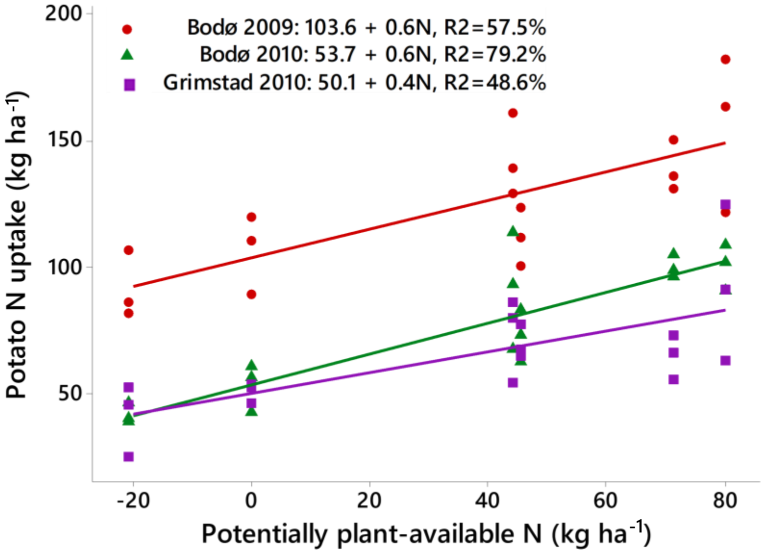
* Treatment codes according to Table 2



Proportion of broccoli yield (%)
>130 mm
110-130 mm
60-100 mm
< 60 mm
Proportion of lettuce yield (%)
>700 g
350-700 g
<350 g
Proportion of potato yield (%)
>70 mm
55-70 mm
40-55 mm
<40 mm
AD1
AD2
SS1
SS2
SM1
SM2
AM1
AM2
MF
NF
Treatments

Figure 1. Size distribution for broccoli, potato and lettuce in a 3-year cropping sequence with anaerobically digested food waste (AD), shrimp shell (SS), sheep manure (SM) and algae meal (AM) as fertilisers at two N application rates (1 and 2), mineral fertiliser (MF) and no fertiliser (NF). For detailed explanation of treatments and measured parameters, see the text and Table 2. Results are means of two locations (Bodø and Grimstad) and of two years for broccoli and potato and values for one year and one location (Bodø) for lettuce.


Bodø 2009: 103.8 + 0.4N, R2=55.0%
Bodø 2010: 49.1 + 0.4N, R2=83.8%
Grimstad 2009: 103.5 + 0.5N, R2=79.6%
Grimstad 2010: 67.0 + 0.4N, R2=63.0%
Broccoli N uptake (kg ha-1)
Potentially plant-available N (kg ha-1)
0
50
100
150
200
250
-50
0
50
100
150
200


Bodø 2009: 103.6 + 0.6N, R2=57.5%
Bodø 2010: 53.7 + 0.6N, R2=79.2%
Grimstad 2010: 50.1 + 0.4N, R2=48.6%
Potato N uptake (kg ha-1)
Potentially plant-available N (kg ha-1)
50
100
150
200
-20
0
20
40
60
80

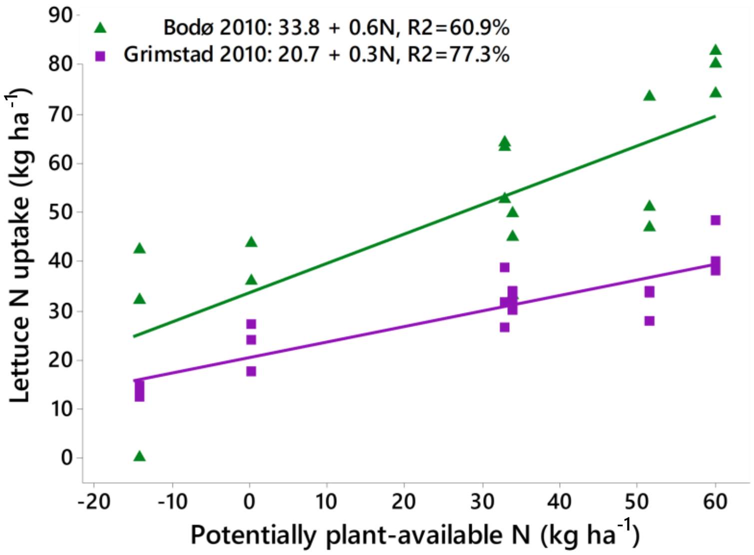

Bodø 2010: 33.8 + 0.6N, R2=60.9%
Grimstad 2010: 20.7 + 0.3N, R2=77.3%
Lettuce N uptake (kg ha-1)
Potentially plant-available N (kg ha-1)
0
10
20
30
40
50
60
70
80
90
-20
-10
0
10
20
30
40
50
60

Figure 2. Measured N uptake in broccoli, potato and lettuce (dots) as a linear function (lines) of potentially plant-available N during the growing season as estimated by Øvsthus et al. (2015) from results obtained by Øvsthus et. al. (manuscript in preparation) during incubation of the fertilisers in soil at controlled temperature and moisture. Results are means for each location and year.

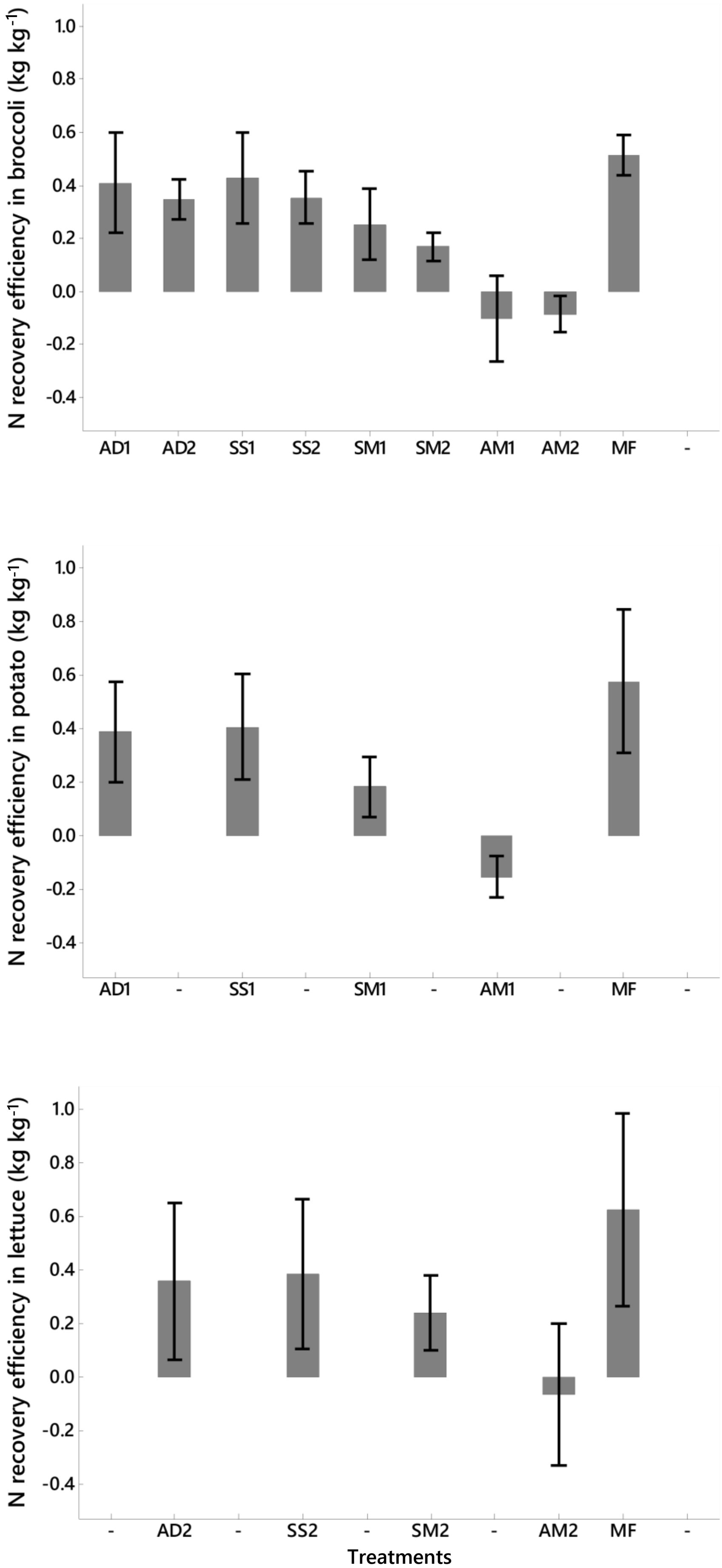

N recovery efficiency in broccoli (kg kg-1)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
AD1
AD2
SS1
SS2
SM1
SM2
AM1
AM2
MF
-
N recovery efficiency in potato (kg kg-1)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
AD1
-
SS1
-
SM1
-
AM1
-
MF
-
N recovery efficiency in lettuce (kg kg-1)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-
AD2
-
SS2
-
SM2
-
AM2
MF
-
Treatments

Figure 3. Recovery efficiency of applied N (NRE = $(U-U_0)/N_A$) for broccoli, potato and lettuce in a 3-year cropping sequence with anaerobically digested food waste (AD), shrimp shell (SS), sheep manure (SM) and algae meal (AM) as fertilisers at two N application rates (1 and 2), mineral fertiliser (MF) and no fertiliser (NF). For detailed explanation of treatments and measured parameters, see the text and Table 2. Results are means of two locations (Bodø and Grimstad) and of two years for broccoli and potato and values for one year for lettuce. The bars show 95% confidence intervals of the mean.