Fertilisation effects of marine-derived residual materials on agricultural crops

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TITLE

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SAMMENDRAG:

«Blågrønt samarbeid» er et viktig stikkord i norsk bioøkonomi, og Møre og Romsdal er et fylke hvor det ligger godt til rette for å utvikle blågrønt samarbeid. Mye av fisken som fanges til videre foredling landes her, og fylket har også en betydelig landbrukssektor og aktive forskningsmiljø innen landbruk og havbruk. Materiale fra havet, som rester av fisk og andre sjødyr, tang og tare, har fra gammelt av blitt brukt til både fôring av husdyr og gjødsling av jordbruksvekster langs kysten. I økologisk landbruk er det et mål å være mest mulig selvforsynt med innsatsmidler til produksjonen, og å resirkulere næringsstoff og organisk materiale. Dette gjelder ikke bare via fôr og husdyrgjødsel internt på gården, men gjerne også ved å tilbakeføre næringsstoff som tapes fra gårdene gjennom salg av produkt og gjennom avrenning. I marin industri er det tilgang på restråstoff, både fra villfanget fisk og makroalger, som per i dag er dårlig utnyttet. Mye næringsrikt materiale går fortsatt tapt ved forbrenning, og mye mer restråstoff fra fisk kunne vært landet hvis det hadde et bruksområde på land. Ved NORSØK har vi arbeidet med marine restråstoff som gjødsel siden 2018. Møre og Romsdal fylkeskommune bevilget et fireårig prosjekt i 2017, «Restråstoffer fra havet som gjødsel til økologisk landbruk» (RESTOR) som med dette leverer sin sluttrapport.

I prosjektet er restråstoff med høyt innhold av bein fra hvitfisk (torsk, sei, hyse, lange, brosme) og restråstoff av grisetang prøvd ut som gjødsel og jordforbedring i forsøk, både innendørs og ute i felt. Gjennomgående har vi sett at fiskebein har hatt en påfallende rask gjødselvirkning i tilførselsåret, og en ettervirkning på nivå med tørket hønsegjødsel. Algefiber, som er rester av grisetang etter kjemisk ekstraksjon for å produsere flytende gjødsel, har en mer langsom gjødselvirkning, men en positivt og langvarig ettervirkning. Algefiber har et innhold av kadmium som gjør at produktet kommer i klasse II som jordforbedringsmiddel. Det er da tillatt å tilføre dyrka jord inntil 2 tonn tørrstoff per dekar over en periode på 10 år. En slik mengde ble brukt i et forsøk med raigras i 2020. Verdien for et forholdstall mellom kalium, magnesium, og kalsium i plantematerialet, på engelsk «tetany ratio», ble da betydelig høyere enn det som regnes for å gi risiko for graskrampe hos drøvtyggere. Vi anbefaler derfor at den tillatte mengden algefiber bør fordeles på minst to tildelinger i løpet av ti år, for å unngå for kraftig opptak av kalium i plantene. Både algefiber og fiskebein er ubalanserte gjødselslag når de tilføres aleine, så det er aktuelt å blande disse produktene. I prosjektet brukte vi et blandingsforhold der 30% av nitrogenet ble tilført i form av algefiber, og 70% i form av fiskebein. Denne blandingsgjødsla ga gode avlinger både i tilførselsåret og i ett eller flere år etterpå.

I løpet av prosjektperioden er det blitt økende interesse for alternative gjødselkilder. De fleste land i Europa er i dag avhengig av å importere både fosfor og kalium fra andre verdensdeler, eller land de er i konflikt med. Det er mye næringsstoff tilgjengelig i råstoff fra havet, men det gjenstår mye arbeid med å finne fram til stabile leveranser og hvordan råstoffene best kan kombineres og håndteres for å bli til gjødselprodukt som kan komplettere eller erstatte dagens gjødselprodukt både for konvensjonell og økologisk dyrking. Det er også behov for lover og forskrifter som er tilpasset en slik gjødsel. Utkastet til ny lovgivning om organiske gjødselmidler i Norge foreslår å innføre grenseverdier for arsen i gjødsel og jordforbedringsmidler. De foreslåtte grenseverdiene vil umuliggjøre bruk av tang og tare til jordforbedring. Her trengs det mer kunnskap for å kunne fastsette riktige nivå.

Arbeidet med å undersøke hvordan marine restråstoff kan brukes til gjødsel fortsetter, både ved NORSØK og hos andre FoU-organisasjoner.

SUMMARY:

This final report from the project “Residual materials from marine industries as fertilisers in organic agriculture” is an example of blue-green collaboration. Such collaboration has been a strategic goal for many Norwegian research and innovation activities since the terms bioeconomy and circular economy came high on the agenda. Significant amounts of residual raw materials from marine industry are still poorly utilized. Traditionally, seaweeds and residues of fish and other sea animals were applied as feed and fertilisers along the coast of Norway, as elsewhere in coastal regions. These valuable materials should still be applied in agriculture, but the application needs to be adapted to a more professional and large-scale production. Organic agriculture aims at being self-sufficient in nutrients and other inputs for the production. A further aim is to recycle nutrients and organic matter not only inside the farm by feeding manure-producing animals, but by recycling nutrients lost from the farm by sales of products, and by runoff and emissions. The RESTOR project (2018-2022) has provided resources for establishing a significant research and developmental work on marine-derived fertilisers at the Norwegian Centre for Organic Agriculture (NORSØK). Marine-derived fertilisers, especially from sustainable collection or capture of natural renewable resources, may fit well to the aims of organic agriculture.

The project has tested residual materials rich in bones from industry processing white fish species (cod, saithe, longfish etc.), and residual material from chemical extraction of rockweed. The materials have been tested as fertilisers and soil amendments, with controlled trials indoor and in the field. A general result is a very rapid growth effect of fishbones in the year of application, with a residual effect in subsequent years resembling that of dried poultry manure. The algae fiber has no immediate fertiliser effect but has a significant residual growth effect. Due to the content of cadmium (Cd), algae fiber is a class II soil amendment product. This implies that it may be applied with up to 20 tons of dry matter per hectare over 10 years, according to Norwegian regulation. An amount close to this level was tested in ryegrass in 2020. The tetany ratio, which is an assessment calculated to assess the risk of tetany in ruminants based on the concentrations of potassium (K), magnesium (Mg), and calcium (Ca) in plant material applied as feed, was then well above the critical level. Hence, we recommend that the material should not be applied at a higher rate than 10 tons per hectare over 5 years (half the maximal rate for each application), to avoid excess uptake of potassium in crop plants. When applied as the single fertiliser material, both fishbones and algae fiber are unbalanced and should be blended with other materials. The project tested a mix where 30% of the nitrogen (N) was derived from algae fiber and 70% from fishbones. This fertiliser gave good yields both in the year of application, and in one or more subsequent growing seasons.

With higher prices on energy, there is increased interest for alternative sources of plant nutrients which may complete existing fossil resources. Most European countries are currently dependent on importing phosphorus (P) and potassium, which is a challenge in a world with increasing levels of conflicts. Significant amounts of nutrients are found in the sea, but we still need both research and developmental work to establish value chains for marine-derived fertilisers which may complete the currently applied fertilisers in both conventional and certified organic agriculture. We also need adapted regulations for such products. A proposal for new regulation on organic fertilisers in Norway includes strict limits for arsenic (As), which may significantly hamper the utilization of seaweed material in fertilisers and for soil amendment. We need more research to assess such limit values.

The R&D work with marine-derived fertilisers is well established, and continues, both at NORSØK and with other research organizations.

COUNTRY:	Norway
COUNTY:	Møre og Romsdal
MUNICIPALITY:	Tingvoll

APPROVED	**PROJECT LEADER**
Turid Strøm	Anne-Kristin Løes
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Preface

This report is the final deliverable from the project “Residual materials from marine industries as fertilisers in organic agriculture” (RESTOR). The project was funded by Møre og Romsdal county council in 2017-2022. The aim was to study if marine residual materials may be combined to a complete organic fertiliser which may supply or replace the current use of conventional poultry manure in organic agriculture. We established contact with local industry partners Algea AS in Kristiansund, Fjordlaks AS in Ålesund and Brødrene Folland AS in Averøy, who delivered materials for testing in several experiments at Tingvoll. The activities in RESTOR were well suited for expansion in spin-off projects. This led to several detailed studies which further expanded the research questions addressed in RESTOR:

“Creating synergies and added value between regional maritime and agricultural research environments” (2019-20) funded by Møre og Romsdal county council, where volumes of residual materials from the blue and green sector in Møre and Romsdal were assessed.

“Seaweed fibre for increased soil organic matter” (FIMO, 2021-2022) funded by the Regional Research Council Møre og Romsdal, where soil health and concentrations in soil and plants of arsenic and other potentially toxic elements (PTEs) were evaluated after application of algae material to soil.

“Pathways to phase-out contentious inputs from organic agriculture in Europe” (Organic-PLUS, 2018-2022) funded by the EU over the Horizon 2020 research program (GA774340), where the effects on the growth of agricultural crops amended with marine-derived fertilisers were thoroughly tested.

“Sustainable utilization of MARine resources to foster GREEN plant production in Europe” (MARIGREEN, 2021-2024) funded by the Research Council of Norway (RCN) and Blue Bio Cofund, where humification of organic materials via composting of marine materials is studied, and marine-derived fertilisers are tested in other European countries.

“Value creation and ecosystem services of European seaweed industry by reducing and handling potentially toxic elements from breeding to soil” (SeaSoil, 2022-2025) funded by the RCN and Blue Bio Cofund, where the potential of seaweed material to sequester C in agricultural soil is studied along with soil-plant dynamics of arsenic and other PTEs.

This significant volume of spin-off activities led to a large volume of results, which was somewhat challenging to present in one report. Due to the various studies conducted it was required to refer many details, but we have tried to draw and **highlight** conclusions wherever possible. We are grateful for the tedious experimental work carried out by many individuals, and we acknowledge the valuable advice and engagement from researchers involved throughout the project, especially Eva Salomon (RISE, Sweden), Jannicke F. Remme (SINTEF, Norway), Egidijus Dauksas (NTNU, Norway) and Annelise Chapman (Tango Seaweed).

Tingvoll, 18.01.23 Anne-Kristin Løes, project leader

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1 Introduction

In coastal regions, fish and seaweed have traditionally been applied for fertilisation purpose in agriculture. Small fishes were buried in potato rows, cod heads were knocked into peat soil grassland, and seaweeds were composted, or mixed into the soil for a rapid decomposition and release of nutrients. They could also be applied as mulch, to cover the soil surface. Utilisation of marine-derived materials as fertilisers in agriculture may be a good approach to recycle nutrients and close the nutrient gaps caused by nutrients and organic matter lost in runoff and sewage. While a broad range of commercial fertiliser products, made from various types of fish and seaweed or their residue are available, significant amounts of materials are still poorly utilised in fish industry (Ahuja et al. 2020). Excess seaweed material on shores may be utilised as biomass (Emadodin et al. 2020; Jones et al. 2020). Growing seaweeds in integrated multi-trophic aquaculture (IMTA), and a rapidly growing interest for application of seaweeds in various products is expected to cause a significant increase in the production of macroalgae (e.g., Khanjani et al. 2022), including seaweed residual materials. Research conducted to increase the value creation from residual materials has often aimed at inventing high-value products. However, with increasing prices for minerals and energy, residual materials may also be relevant in bulk products with lower commercial value but high importance, such as fertilisers. Fertilisers made from organic materials which are currently wasted are relevant for certified organic growing, where synthetic mineral nitrogen fertilisers are prohibited (EC 2018), and the use of other mineral fertilisers is also restricted.

The background for this study was a research effort under the headline of bioeconomy. Fishing and aquaculture are two significant industries in Norway, and collaboration between the marine (blue) and agricultural (green) sector has been a strategic target for Norwegian bioeconomy research (Regjeringen 2016). Making complete fertilisers from currently wasted marine-derived materials is an example of blue-green collaboration and innovation.

About 100 years ago, several factories producing “guano” fertiliser from fish heads and other marine animal materials were located along the Norwegian coast (Picture 1), and fertilisers made from wild seaweed are still produced and exported from Norway. Commercial fertiliser products from seaweed may be dry materials, grinded or pelleted, possibly after composting; or liquid extracts (RHS 2022). The recommendations from fertiliser producers emphasise the rich content of a range of minerals, and positive effects on soil characteristics, such as increased water retention. From a plant nutrient perspective, the high content of potassium (K) is of special importance. Fish-based fertilisers are dry or liquid products made from drying or hydrolysis of grinded fish waste material such as backbones, heads, skin, and intestines. Dry products are commonly marketed as meals, and liquid products are categorised as emulsions or hydrolysates (FertilizerHub 2022). The meals are recommended as a source of nitrogen (N) and phosphorus (P), whereas liquid products are recommended to give crop plants a quick boost of N.

The effects of seaweed and fish-derived materials on the growth of crop plants has been reviewed e.g., by Nabti et al. (2017) and Ahuja et al. (2020). Seaweed fertilisers are often applied for beneficial effects on plant growth and quality which come in addition to the growth response achieved by the nutrients contained in the material. The difference between such bio-stimulating effects and general plant growth is challenging to define precisely. Seaweeds contain organic molecules which may affect crop plants, the characteristics of soil or other growing media, and associated organisms.

Picture 1. Guano factory at Steilnes around 1915. Source: Finnmark county library 2022. Photo by Jakob Lauritz Smith Bredrup.

Modern farmers demand complete fertilisers with a stable effect, which are easy to handle. Hence, it is not straightforward to replace complete commercial fertilisers by marine-derived materials. At the Norwegian Centre for Organic Agriculture (NORSØK), we have worked with residual marine materials derived from local industry partners since 2018. Materials have been tested in pot and field experiments, with chemical analyses of soil and plants and measurements of crop growth. In this report, we present the results that were achieved over five years of experimental work with marine-derived fertilisers (2018-2022).

The first experimental study with residual marine materials for fertilisation of crop plants at NORSØK was an indoor pot experiment, conducted in 2018 (Ahuja & Løes 2019). The growth of ryegrass in a low-P mineral soil fertilised with algae fibre and fish bones was studied with five repeated harvests, after one initial fertilisation. Calcium nitrate fertiliser was applied as a positive control. In total, across two N levels equal to 300 and 600 kg N ha^{-1} applied at the onset of the experiment, the accumulated above-ground yield was 3.3 g dry matter (DM) per pot for fishbones, and 2.2 without any fertiliser. Algae fibre and calcium nitrate gave a similar average yield of 2.6 g DM per pot. Whereas the growth effect of fishbones was very rapid, algae fibre had a long-term effect. The effect of fertiliser rate was mostly not significant.

The experimental work proceeded with field studies in 2019 and 2020, and residual effects measured during 2020-2022. In 2019, we conducted a combined pot- and plot experiment in the field with oats and leek as test crops, and in 2020 a field plot experiment with ryegrass.

The present report provides information about the characteristics of marine-derived residual materials which were applied. We further describe the experimental design of the field experiments, with results achieved for crop yield levels and concentrations of plant nutrients and potentially toxic elements (PTEs). We also present effects of fertilisation on the nutrient concentrations and pH in soil. The classification of fertiliser materials as soil amendments with respect to concentrations of PTEs, with implications for the amounts to be applied per unit area in the field, are discussed in separate sections towards the end of the main chapter presenting results for crop yields and element concentrations in soil and plants. It was not possible to include the many results of soil and plan analysis in tables in the main text. These results are shown as Appendix 1, 2 and 3, each containing several tables of average element concentrations in soil and plant material. A file presenting the data on a more detailed level (when samples were not bulked across treatment), is provided in Organic E-prints (www.orgprints.org) at the same address (entry) as the present report.

In a separate chapter towards the end, we have referred a study where fertiliser materials were buried in the soil during the growing season of 2020, and regularly harvested to observe the decomposition over time.

The report is very long, and conclusions have been drawn when relevant, **highlighted in bold**, and compiled in a final chapter along with recommendations for further research.

The overall aim of this report is to describe the research efforts which were conducted, and what we have learned from these efforts. We hope that this will provide knowledge required for a broader application of marine-derived materials in agriculture.

2 Materials and methods

2.1 Residual materials from marine industry

Fertilisers from organic materials have traditionally been made from residual materials which cannot be applied for food or feed purpose, such as animal bones, horns, bristles, and feathers. The significant increase in certified organic production over the last decades has led to a large industry which is producing commercial fertilisers from such materials. Assessed per kg of nutrient, the prices of nutrients in fertilisers are very low compared with feed and food products. Hence, residual materials for application as fertilisers in the present study were searched for from nearby marine industry, as leftover materials being disposed of as organic waste. In Norway, such disposal usually implies incineration or anaerobic digestion.

A significant volume of residual seaweed material is available at Algea AS, Kristiansund. This industry applies a species of brown macroalgae, rockweed (*Ascophyllum nodosum*) that is harvested along the Norwegian coast, dried, grinded, and extracted by acids and alkali to produce a liquid fertiliser extract. The remaining filter cake, further called algae fibre (Picture 2), is a black paste with 25-30% dry matter (DM), with very fine particles and a high content of essential plant nutrients such as potassium (K) and magnesium (Mg) (Table 4), but also significant concentrations of some potentially toxic elements such as arsenic (As) and cadmium (Cd).

Picture 2. Algae fibre from Algea AS, Kristiansund. The product is a residue after chemical extraction of rockweed for liquid fertiliser and is a paste with about 25% dry matter. Photo by Ishita Ahuja.

Two types of algae fibre are available, where one is extracted with nitric acid (HNO_3) and thus has a higher content of N (Table 4; Zikeli et al. 2022). In our field studies, the high N-type of algae fibre was applied, which was delivered from the production plant in international plastic containers (IPC) in late April 2019. Representative samples were sent for analysis at Eurofins. In 2020, new algae fibre material was delivered in late April, and sampled for analysis at Nemko Norlab (Namsos, Norway).

For fish residues, significant volumes of poorly utilised materials suitable for fertilisation purposes can be found in the “white fish” sector (captured fish like cod, saithe etc.). Fish residual materials were delivered from clip fish industry partners; Fjordlaks AS in Ålesund and Brødrene Folland AS in Averøy, Norway. After preparation of fish for salting and drying, backbones, heads and other residues may be grinded and further processed. One processing option is to acidify the grinded fish, commonly by formic acid to pH <4, and store it in a tank for hydrolysis. Layers of liquid (fat on top of hydrolysed protein) will develop over time and may be pumped off and applied for feed in aquaculture. At the bottom of the tank, a sediment with mostly bone particles will precipitate, and this material is currently disposed of as organic waste. Another processing option is to dry the fish before or during grinding. Fish bone particles may then be separated from other tissue by sieving. Fresh fishbones may also be grinded and applied in field.

Fish bones contain high proportions of essential plant nutrients such as N, P, and calcium (Ca), and complement the nutrient content in seaweed. In the present study, acidified sediment from white fish, and freshly grinded white fish backbones were applied.

Since the hydrolysis tanks are not emptied very often, sediments are not easy to acquire. Hence, the same batch of material, delivered in October 2018, was applied in 2019 and 2020. Acidified sediment was delivered from Fjordlaks in two containers (IPC) with the top cut off, each containing about 800 litres of material (Picture 3).

During storage, the containers were kept in shade, and well covered. Three representative samples from each container were analysed in February 2019 (Eurofins, Table 3). For each container, one sample was sent frozen overnight and dried at room temperature in the laboratory; one was dried at 40 °C at NORSØK; and one was dried at 105 °C at NORSØK, before sending the dried sampled to the laboratory. For application in field in 2019, material from container 1 was dried by placing it on a plastic sheet on the floor in a well-ventilated building and moving it regularly by a rake for about 3 weeks during April 2019. The material was then sieved (1.4 cm x 2.8 cm) to remove coarse particles and facilitate even spreading in the field (Picture 4). A representative sample of the material for chemical analysis (Eurofins, Table 3) was taken in late April 2019.

Picture 3. Sediment from hydrolysis of grinded residues of white fish (cod, saithe etc.) from Fjordlaks AS, ca. 50% dry matter. October 2018. Photo by Anne deBoer.

For drying in 2020, one batch of material from container 2 was dried on the floor, and another in a drying cabinet. After sieving off coarse particles, each portion of acidified fishbone fertiliser was made with 27% of material from the cabinet and 73 % from the floor. Representative samples of each material were analysed by Nemko Norlab (Table 3).

In April 2020, frozen backbones of cod (*Gadus morhua*) and longfish (*Molva molva*) were collected from Br. Folland. Thawed backbones were grinded by an electric grinder (5 mm), frozen, and thawed the day before application in field. The grinded material was soft and wet and could be spread quite evenly in the field by hand (Picture 4). A representative sample was analysed at Nemko Norlab, and several additional samples were analysed to study if drying affected the concentration of total N in the dry matter (DM). At Eurofins, all samples are dried before determination of total N, and we feared that this might affect the N concentration. Nemko Norlab could determine total N without initial drying.

Picture 4. Fish residual material applied as fertilisers in field trial 2020. Left side: sediments from grinded, acidified and hydrolysed fish residues (backbones, heads etc. of various fish species used for clip fish). Right side: freshly grinded backbones of similar fish species. Photos by Anne deBoer.

The analyses of fertiliser materials were performed at Eurofins, or at Nemko Norlab. pH was measured in dried and milled samples after addition of deionized water (v:v 1:2.5). For total C, thermal decomposition at 1200–1500 °C to convert all carbon into CO_2 was applied in a total organic carbon analyzer, including a step to measure CO_2 by a detector, following NS-EN 15936: 2012. For total N, the Kjeldahl method was applied, where all N is converted to ammonium sulphate by application of concentrated sulfuric acid, converting ammonium to ammonia gas by application of sodium hydroxide and measuring the amount of ammonia by distillation into hydrochloric acid and measuring the amount of acid not reacting with ammonia. The concentration of ammonia was measured by a photometric reaction (thymol blue) after acidification by sulfuric acid. By multi-element determination of selected elements (P, K, Ca, Mg, S, Cl, As, Cd etc.) by inductively coupled plasma mass spectrometry (ICP-MS; internal method based on NS-EN ISO 17294-2: 2016), the sample is chemically digested by a nitric acid/hydrogen peroxide solution at 120 °C for 30 minutes to bring ions into aquatic solution, followed by a quantitative assessment of concentrations of elements by the measuring instrument.

2.2 Pot experiment with oats and leek, 2019

In the growing season of 2019, a combined pot and plot experiment was conducted in the field, with oats and leek as test crops. A pot experiment allowed for comparing two levels of fertiliser application, Low (**L**) and High (**H**), with two different crops (leek and oats). In the plot experiment, we tested one level of fertiliser, and one crop (oats).

The pot experiment compared 10 fertilised treatments, and one unfertilised **Control**. High-N algae fibre (**Alg**) and acidified white fish sediment from hydrolysis (**Fish**) were applied as single materials, or in a combination (**Mix**) where 70% of the N was derived from Fish and 30% from Alg. Two positive controls were tested; calcium nitrate (Calcinite, Yara; abbreviated **Nmin**), and compound organic fertiliser made from dried poultry manure enriched with meat-and-bone meal and vinasse (Grønn Øko 8-3-5, Grønn Gjødsel; abbreviated **Norg**).

The fertilisation aimed for application of equal amounts of total N, to be applied in a low and a high rate for each crop, corresponding to 80 and 160 kg N ha^{-1} for oats, and 160 and 320 kg N ha^{-1} for leek. The soil has a high content of organic matter and hence a field bulk density of about 1 kg dm^{-3} (Løes et al. 2013). The amount of N applied per pot with 8.6 litre of soil was planned to comprise 0.34 g for the fertilisation rate of 80, 0.69 g for 160 and 1.38 g for 320 kg N ha^{-1}. The value of 0.34 g was achieved by transforming kg N per hectare (ha) to g N per litre of soil:

80 kg N in fertiliser applied to a topsoil layer of 0.2 m depth with a bulk density of 1 kg per litre

= 80 kg N/(0.2 m x 10 000 m^2) = 0.04 kg N per m^3 soil = 0.04 g N per litre soil

0.04 g N dm^{-3} x 8.6 dm^{-3}= 0.344 g N per pot for 80 kg N ha^{-1}

0.344 x 2 = 0.69 g N per pot for 160 kg N ha^{-1}

0.344 x 4 = 1.38 g N per pot for 320 kg N ha^{-1}

Table 1. Target values of N application in a combined pot and field trial in 2019, compared with amounts of various fertiliser materials applied and actual amounts of N on a kg per hectare level. Pot size = 8.6 litre of soil.

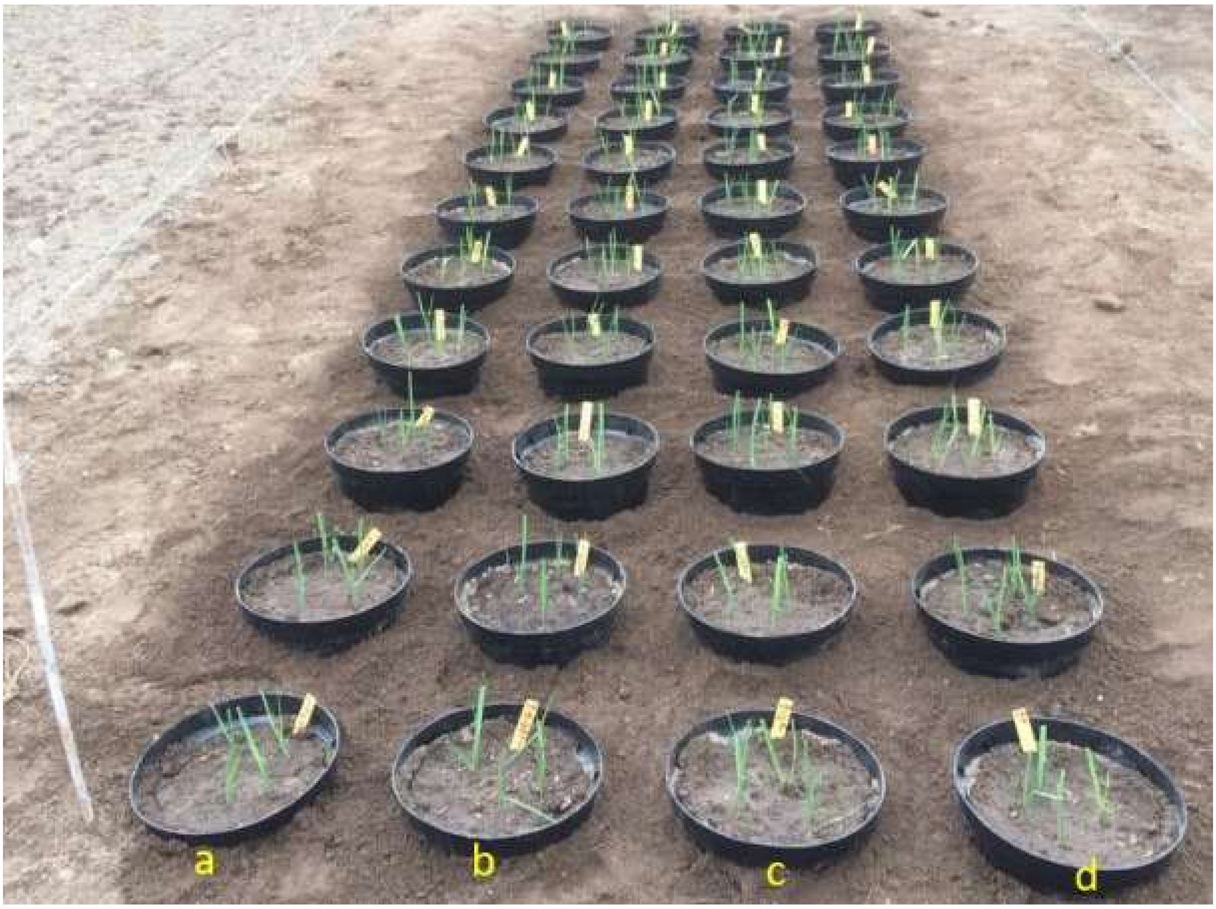
Target N amount	g N/pot			kg N/ha		
	0.34	0.69	1.38	80	160	320
Material	*g material/pot*			*kg N/ha*		
Calcinite, Nmin	2.2	4.5	9.0	80	162	324
Poultry manure, Norg	4.3	8.6	17.2	75	151	302
Acidif. fish, Fish	5.7	11.4	22.8	33	67	133
Algae fibre, Alg	87.0	174.0	348.0	59	117	235
70% Fish + 30% Alg, Mix	4+26	8+52	16+104	41	82	164

The amounts of fertiliser material which were applied per pot are shown in Table 1. The applied amounts were based on the analytical values for total N concentration and dry matter content available by April 2019, and for the poultry manure it was based on the N concentration given by the producer. The actual concentrations of total N (% DM) were measured after the fertilisation, and for the fish material, the value in 2019 was significantly lower than expected (see section 3.1 and 3.2). Hence, for Fish and Mix, significantly less N than the target level was applied. These lower values pertain also for the plot experiment with oats, described in section 2.4.

The previous crop on the field site that was used for the pot experiment was a 4th year grass-clover ley which was ploughed on April 26, 2019. Soil for filling of pots was dug up from the topsoil layer (0-20 cm), well mixed and sieved (5 mm). One pit was dug out to fill pots to be applied for oats, and another for filling pots to be applied for leek. The pits were used for placing the filled pots (Picture 5), one for oats and one for leek. The soil batch prepared for pots with leek had 8.2% loss on ignition (LOI) whereas the batch prepared for pots with oats, located slightly lower in the slope of the field, had 6.3% LOI. Portions of soil, 9.7 kg for pots with leek and 10.1 kg for pots with oats, were mixed with fertiliser materials before pots were carefully packed with three steps of partwise filling and gently tapping of the pot against a table, to ensure equal physical conditions. A nylon net in the bottom of the pots prevented soil loss and potential growth of roots outside the pots. The pots were 22 cm high with a top diameter of 27 cm and contained 8.6 litre of soil.

30 seeds of oats (*Avena sativa* L., cv. Niklas) were planted per pot on May 24, and covered by a small volume of the test soil. Germination occurred rapidly and evenly across treatments, with 27 plants per pot as the minimum average germination rate obtained (in **Nmin_H**) and 29 plants per pot as an average for all treatments, recorded on June 5. Four plants of leek (*Allium porrum* L. cv. Lancelot) were planted per pot on May 24. 900 ml of tap water was applied per pot directly after planting. The smallest plant in each pot was removed on June 21. The leek pots were irrigated on July 31 and August 6, applying 1 litre of tap water per pot on each date. Weeds in the leek pots were removed by forceps.

The pots were placed in rows comprising four pots a, b, c, d (Picture 5), with the top placed horizontally about 5 cm above the surface, aiming for a similar level of soil surface inside and outside of the pots. The area around the pots was covered by woodchips to reduce the growth of weeds and avoid breaking of pots. The distance between pots was 9 cm within rows, and 14 cm between rows. The four lines of pots parallel to the long sides of the pit (a-d) were treated as blocks. One pot per treatment were arranged in random order in each block.



Picture 5. Pots with leek plants arranged in four blocks a-d, before covering the soil surface with woodchips, May 27, 2019. Photo by Anne-Kristin Løes.

2.3 Crop characteristics and plant and soil element concentrations

The harvest date aimed at recording the maximal dry matter (DM) production of the plants, which for oats is the late flowering stage. Oat plants were harvested on July 24, 2019. For leek plants, the growth continued over a much longer period and the harvest was done when some leaves started to senescence, on September 3. At harvest, pots with plants were removed from the site and brought to the laboratory. For oat plants, the fresh weight of aboveground plant material was recorded, and the dry weight after drying to constant weight at 60 °C. Plants were cut at the soil surface. For leek, fresh weights of individual plants were recorded after roots had been cut off. Fresh and dry weights of plant material (without roots) was recorded per pot after drying to constant weight at 60 °C. In one pot of the Control treatment, one plant had died off. In one pot of the treatment Mix_H, two plants were bolting. The records from these plants were not included in the statistical analysis.

For chemical analyses, the aboveground plant material from each replicate pot was compiled into one sample per treatment. Milling of the plant material, and chemical analysis was conducted by Activation Laboratories (Actlabs), Ancaster, Canada. Plant nutrients were analysed by the Plant Tissue Analytical Package, which includes N, P, K, Mg, Ca, Na, S, Fe, Al, Mn, B, Cu, and Zn. Additionally, As, Cd, Co, Cr, Cu, Pb, Hg, Mo and Ni were analysed by a Heavy Metal Package. Macro and micronutrients and potentially toxic elements (PTEs) were extracted by nitric acid/peroxide digestion. Total N was analysed by combustion (AOAC 990.03). P, S, K, Mg, Ca, Na, Fe, B, Cu, Mn, and Zn were analysed by inductively coupled plasma optical emission spectrometry (ICP-OES). The minerals Mo, Se, Co, Al, Ni, Cr, As, Cd, Hg and Pb were analysed by ICP-MS.

From the experimental soil, one representative sample for chemical analysis was taken from each batch of soil on May 24, and analysed for pH (H_2O), AL-extractable P, K, Mg, Ca and Na, acid-soluble K (HNO_3), Olsen-P (bicarbonate), and potentially toxic elements. After harvest, the soil in each pot was mixed carefully in a container and a representative sample per pot was analysed for pH, AL-extractable nutrients, and acid-soluble K, whereas PTEs were analysed per treatment, in bulked samples. Soil analyses were conducted by Eurofins. Extraction by ammonium lactate–acetate (AL) solution is the standard method in Norway and Sweden to assess the plant availability of P, K, Ca, Mg and Na. Dried soil is extracted by a mixture of 0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75, and upon filtration the concentrations of nutrients are measured by ICP-MS.

2.4 Plot experiment with oats, 2019

The weather in the growing season of 2019 was acceptable for the growth of experimental crops. A precipitation of 355 mm was recorded between May 24 and September 3 on a nearby climate station in Surnadal. The site applied for the plot experiment was adjacent to the pot experiment pits, and the previous crop was the same. Ploughing and soil tillage was conducted by tractor and a horizontal rotavator. After plot-wise sampling of topsoil (0-20 cm, 6 soil samples per plot), fertilisers were applied by hand to the tilled soil on May 14-15 and incorporated by a hand rake on May 16. The plot size was 2 m x 8 m, and five treatments were randomly distributed in four replicate blocks, divided by 2 m wide areas. The test crop was oats, and the fertiliser rate was the High rate of 160 kg total N ha^{-1}, equal to what was applied in the pot experiment (Table 1). To calculate the amount of fertiliser materials applied per m^2 in the field experiment, the amounts applied per pot may be divided by 8.6

(8.6 litre soil per pot) and multiplied by 200 (200 litre topsoil per m^2). Four treatments, Norg, Fish, Alg and Mix, were compared with an unfertilised Control, with details as described for the pot experiment in section 2.2.

Seeds of oats (cv. Niklas) were planted by tractor and a sowing machine on May 21. Concurrently, seeds for a new perennial ley were planted, which was a commercial mixture of grass and clover species (Strand no. 30 Sørlig Øko). The types and amounts of seeds were similar to what the farmer renting the NORSØK land normally applies for re-establishment of the ley. On May 30, the oats germinated. The harvesting of oats occurred on July 31, when the plants were flowering (Picture 6).

Picture 6. Above: Field plots shortly after germination of the oat plants, June 12, 2019. Below: Harvesting the field, July 31, 2019. Photos by Anne-Kristin Løes.

A harvest plot sized 1.2 m x 7 m (approximately) was cut, the exact measures were recorded, and the fresh weights were recorded in field. For determination of dry matter (DM, %), a representative sample was taken from each plot and dried at 60 °C to constant weight. One representative sample per plot was also taken for chemical analysis, and was milled and analysed by Actlabs, see details in section 2.3. There was a significant growth of weeds, and a botanical analysis was carried out by hand-sorting about 1 kg of representative plant material per plot at harvest into oats, grass + weeds, and clover. In the growing seasons of 2020, 2021 and 2022, the yields of the perennial grass-clover ley established in 2019 was recorded with two cuts per season, as described above, to measure the residual effects of the fertilisers applied in 2019. The harvesting dates were June 16 and August 20 in 2020; June 16 and August 11 in 2021; June 6 and August 23 in 2022.

Soil samples from May 2019 were analysed plot-wise for pH, AL-extractable nutrients, acid-soluble K, Olsen-P and PTEs by Eurofins as described in section 2.3. A new set of soil samples were taken from each plot after the second harvest of ley in 2020 and analysed for the same characteristics at Nemko Norlab.

2.5 Field experiment with ryegrass, 2020

In April 2020, a site for another field experiment was located on the same field, 40 m from the experimental plots with ley (2020-2022) where fertilisers were applied in 2019. The new site, which was used by the local farmer for growing oats as a cover crop for re-establishment of ley in 2019, was ploughed by tractor on April 23 and tilled by tractor and horizonal rotavator on April 28. On April 30, soil samples (0-20 cm, 6 per plot) were taken from each experimental plot. Fertilisers were applied by hand during May 25-26 and incorporated by a manual rotavator; amounts are shown in Table 2. Seeds of annual ryegrass (*Lolium westerwoldicum* cv. Caremo) were planted by a 1.5 m wide experimental sowing machine on June 2. Experimental plots were sized 1.5 m x 8 m, and four replicate blocks were divided by 2 m wide stripes across the slope of the field (Picture 7).

Eight treatments were compared with an unfertilised Control in this experiment, including the materials tested in 2019 (**Norg, Fish, Alg, Mix**; described in section 2.2). Norg, Fish and Mix were tested with low (**L**) and high (**H**) rates of N, aiming for 300 and 600 kg total N ha^{-1}. This is a very high rate of fertiliser, but we wanted to test the same level which was applied in the indoor pot experiment with ryegrass in 2018 (Ahuja & Løes 2019). Algae fibre (Alg) could only be applied with the low N rate, since a higher rate would likely have caused poor germination of seeds, as the material has a pH about 9 (Table 4). In addition to the acidified fish sediment (Fish), we tested freshly grinded backbones of cod and longfish (*Molva molva*), abbreviated **Frish**. For this material it could be a risk of that the high application rate would cause problems e.g., with flies or odour. Hence, we only tested this material with the low rate of N. As shown in Table 2, the actual amounts applied were closer to the target rates of total N in 2020 than in 2019.

Table 2. Amounts of various fertiliser materials applied in a field trial in 2020, and actual amounts of N applied on a kg per hectare level. Plot size = 16 m^2.

Material	Low	High	Low	High
	kg material/plot		kg N/ha	
Poultry manure. **Norg**	5.1	10.3	300.2	600.4
Acidif. fish. **Fish**	10.3	20.5	282.0	588.0
Algae fibre. **Alg**	112.0	--	435.0	--
70% Fish + 30% Alg. **Mix**	7.2+33.6	14.4+67.3	329.0	673.0
Fresh fishbone. **Frish**	14.3	--	300.0	--

Four cuts of ryegrass were conducted (Picture 7), on June 30, July 20, August 14, and September 21. For the 2nd, 3rd and 4th cut, the fresh weight of the canopy from a harvest plot inside each experimental plot was recorded in the field, and the DM was determined for representative plot-wise samples, as described in section 2.4. At the 1st cut, the plants were very small, and the aboveground plant material was cut off near the soil surface by scissors within three randomly located frames sized 0.5 m^2 in each plot and weighed. The samples were sorted by hand into grass and weed plant material, and the proportion of weeds was calculated (% of dry weight, DW).

Picture 7. Preparing the third cut of ryegrass in a field experiment fertilised with marine-derived materials, August 12, 2020. Photo by Anne-Kristin Løes.

Chemical analysis of the ryegrass material was conducted for samples compiled for each treatment, per harvest date; totally 4 x 9 samples. In October 2020, 6 soil samples per plot were compiled for chemical analyses. Analyses of plant material and soil sampled in autumn were conducted by Nemko Norlab, Namsos, whereas soil samples from spring 2020 were analysed by Eurofins.

In the growing season of 2021, potatoes were grown on the "Ryegrass 2020"-experimental site in three replicate blocks, to study if the concentration of arsenic in the tubers was increased by the application of algae fibre in 2020. On the fourth block, oats were grown and harvested as green fodder. All plots were equally fertilised by dried poultry manure corresponding to 120 kg total N ha^{-1};

potatoes were given an additional dressing of mineral potassium fertiliser. The details are presented in Løes et al. (2022a). In 2022, perennial ley was established on the experimental plots, and one cut was conducted, on August 29.

2.6 Statistical analyses

Statistical analyses were performed using Minitab Statistical Software. We used a general linear model (GLM) to test whether yield (kg DM ha^{-1}) of each crop (ley, ryegrass, leek, oats, potato), soil characteristics or plant nutrient concentrations were affected by the treatments (fertiliser type plus rate). Differences between mean values were considered statistically significant at $p < 0.05$ and mentioned as tendencies at $0.05 \leq p < 0.1$. When significant, the differences between the means of the treatments were tested using the Tukey t-test.

For plot-wise soil samples in spring and autumn of 2020, a general linear model was applied to study if changes from spring to autumn within each treatment (season x treatment) were significant on a 5% level.

3 Commented results

3.1 Chemical characteristics of fishbone material in 2019

For a safe preservation, formic acid is applied to grinded fish to pH < 4.0 during hydrolysis, forming a sediment to be removed from the industrial tanks when required. For the fishbone material in two containers (IPC) shipped to NORSØK in October 2018, some additional formic acid was applied before transport, and when the containers were first opened, in January 2019, the pH was 2.45 in container 1 and 2.76 in container 2. The material was sampled for analysis, and for two samples per container the DM content of fresh material, recorded at NORSØK was 50.0 and 53.3 % for container 1. For container 2, it was 52.1 and 54.7 %.

One representative sample from each container was divided into aliquots, where one was frozen, one was dried at 40 °C in an actively ventilated drying cabinet, and one was dried at 105 °C in a small drying cabinet with passive outlet of hot air. The six frozen or dried samples were sent to Eurofins (overnight) for analysis (Table 3). At Eurofins, all samples were dried at 25 °C with circulating, de-watered air, and DM content recorded for the fresh (frozen) and dry samples.

Fishbones are rich in calcium and hence have a high buffering capacity. Hence, after being dried and milled in the laboratory, the pH was 4.1 for material taken from container 1, and 4.4 for material taken from container 2 (Table 3). For fishbones initially dried at NORSØK, the pH of milled bones was somewhat higher (4.9-5.1), indicating that some ammonium (NH_4) may have been lost as NH_3 gas.

The concentration of total N in the grinded and acidified fish material was surprisingly high in the frozen material that was dried in the lab, 133 and 153 g total N kg^{-1} DM (Table 3). Toppe et al. (2007) found 63 g total N kg^{-1} lipid-free DM in bones from cod, and 63.8 for saithe, after cleaning the fish bones by scraping, boiling in water and removal of visible soft tissue by water rinsing before analysis. Less soft tissues in the materials analysed by Toppe et al. (2007) may explain the higher values found here. The much lower values of total N in samples dried at NORSØK indicate that significant losses of N may occur during such drying when the initial values are high. Somewhat higher concentration of NH_4 in samples dried at 40 °C as compared with 105 °C indicates that amides (with ammonia, NH_4) may have been produced at this temperature, whereas at 25 °C the concentration of NH_4 was lower.

The content of total C was quite variable, ranging from 13 to 22 %, with no clear effect of drying method. The fishbone material is heterogenous, being comprised of bone particles with carbonates and carbon from non-hydrolyzed soft tissues.

While the concentrations of total P come quite close to values presented by Toppe et al. (2007) for bones of cod and saithe (*Pollachius virens*), 113 and 108 g P kg^{-1}, the concentrations of Ca were somewhat lower. Toppe et al. (2007) found 190 g Ca kg^{-1} lipid-free DM for cod and 199 for saithe. Somewhat lower values in our material may be due to some dissolution of calcium during hydrolysis at pH < 4.

Since the results indicated that drying at 40 or 105 °C could reduce the N content of the fishbones significantly, we arranged a careful drying for the material to be applied in the field study, trying to mimic Eurofins conditions. A batch of about 200 kg of sediment was placed on a plastic sheet on the concrete floor of a well-ventilated building in April 2019, and regularly turned by a hand rake (Picture 8). We assumed that the material would have a total N concentration of 5% of the DM, comparable to values found for dried material sampled in January 2019 (Table 3). However, when this material was analysed, the value was much lower than expected, being only 2.88 % of DM, or 29 mg kg^{-1} (Table 3, bold line container 1). It seems that the drying had made the N highly available to plants, since the concentration of ammonium was 10% of the total N, which was higher than found for previous samples.

Picture 8. Sediments of grinded, hydrolysed white fish (cod, saithe etc.) dried on a plastic sheet spread on the floor, April 2019. Photo by Anne-Kristin Løes.

The acidified fishbone material was subject to several subsequent analyses, and the average values of data available by November 2022 are shown in Table 4. A complete overview of all analysed characteristics such as potentially toxic elements and the range of variation for each characteristic when more than one analysis was performed, is shown in Zikeli et al. (2022).

Table 3. Characteristics of sediments of hydrolysed grinded, acidified residual materials of "white fish" (cod, saithe, longfish) from two batches (IPC tanks), after different drying procedures at Eurofins (E) or NORSØK (N). Bottom lines in ***bold and italics*** *are for materials dried on floor for use in field 2019 (tank 1) and 2020 (tank 2). Loss on ignition (LOI) and total C are given as % of DM; nutrient concentrations = g kg^{-1} dry matter (DM).*

Tank	E or N, °C	pH	DM %	LOI	Tot-C	Tot-N	NH_4	Tot-P	P-AL	Tot-Ca	Tot-K	Tot-Mg
1	E, 25	4.1	47.5	42	12.7	133	1.38	110	36	130	0.80	0.8
1	N, 40	4.9	90.4	44	20.4	50	2.51	100	19	120	1.10	0.9
1	N, 105	5.1	97.8	40	16.9	40	1.84	110	16	130	1.20	1.1
2	E, 25	4.4	49.5	47	18.4	153	1.68	110	34	130	0.80	1.1
2	N, 40	4.9	89.3	47	21.8	59	2.49	94	18	130	1.20	1.2
2	N, 105	5.1	98.0	43	18.1	41	1.91	96	16	120	1.20	1.2
1	***N, < 25***	***5.0***	***87.3***	***40***	***13.8***	***29***	***2.96***	***69***	***86***	***110***	***1.30***	***1.0***
2	***N, < 25***	***-***	***80.0***	***-***	***-***	***41***	***-***	***93***	***-***	***160***	***1.10***	***0.8***
2	***N, 40***	***-***	***85.0***	***-***	***-***	***44***	***-***	***100***	***-***	***170***	***1.10***	***0.8***

3.2 Chemical characteristics of fishbone material in 2020

In February 2020, one sample from each container was frozen, sent from NORSØK and analysed at Eurofins. pH was then 4.6-4.7, and the total N concentration 36 and 47 g kg^{-1} DM. To exclude that these values, significantly lower than for samples taken in January 2019, could somehow be caused by the drying process, we searched for a laboratory where the analyses of total N could be done on moist materials. We found this possibility at Nemko Norlab, Namsos. For samples of fish sediment analysed at Nemko Norlab in May 2020, total N was measured both without initial drying of the sample, and after drying at 105 °C. **The values were not lower after drying**. For three aliquots of fish sediment, the tot-N concentration was 49, 45 and 40 g kg^{-1} DM before drying, and 41, 45 and 43 g after drying.

For application in the field experiment in 2020, the material was again dried on floor plus in a drying cabinet. These materials had 41 and 44 g tot-N kg^{-1} DM (Table 3), which is comparable to the values found after drying at NORSØK in January 2019, and to the values found for the aliquots measured before and after drying at Nemko. The measurement uncertainty for total N at Nemko Norlab was 15%. This leads to the conclusion that **the N content of the sediment had stabilised at about 4% of DM after a period of storage, although initially, it was significantly higher**. It is well possible that N was emitted from the tanks during storage, even if they were mostly covered by a plastic wrapping.

One sample of fresh grinded white fish backbone, when analysed fresh, had a tot-N concentration of 110 g tot-N kg^{-1} DM, and after drying 94 g tot-N kg^{-1} DM. This may indicate that fresh fish material may lose N during drying. However, for 9 samples of about 500 g fresh grinded backbones (with significant amount of soft tissue attached to them), which were dried in a thin layer in a plastic tray with highly different conditions, the highest total N concentration, 130 g kg^{-1} DM, was achieved for one sample dried at 40 °C with no air circulation (Ahuja et al. 2021). With these conditions we could assume that some degradation of proteins leading to emission of ammonia could occur. All the remaining samples had 110 g total N kg^{-1} DM, except one sample, dried at 25 °C with intensive air circulation, which had 54 g total N kg^{-1} DM.

These analytical values indicate that **it is possible to lose N by drying of acidified or fresh grinded fish material, but that in most cases, drying will not reduce the concentration of tot-N.** The highest tot-N concentration found in fresh grinded backbones of white fish at Nemko Norlab in May 2020, 130 g kg^{-1} DM, was comparable with the high values found for the acidified fish material in January 2019, analysed by Eurofins (Table 3). The values are comparable with the data reported by Jafarpour et al. (2020), who found 9.8-12.6 % tot-N in cod frames (backbones with soft tissues) sampled in various months during 2017-2018. For the field experiment in 2020, we assume that 110 g tot-N kg^{-1} DM was present in fresh grinded backbones of white fish (Table 4).

Conclusion: It should be further studied whether the initially high concentrations of tot-N found in relatively fresh acidified fish sediment (Table 3) are representative for this type of material when it is recently removed from hydrolysis tanks. Further, to maximise the utilisation of this valuable plant nutrient, we need to clarify which conditions may lead to losses of N during storage of fish material.

3.3 Chemical characteristics of algae fibre in 2019 and 2020

Whereas the fish residues applied in the present study were quite diverse, being comprised of various species of white fish from different locations and captured at different seasons, the algae fibre is a result of a process where batches of dried and grinded seaweed from different locations and seasons are mixed according to chemical characteristics to keep the composition of the commercial product (fertiliser extract) stable. This implies that the algae fibre residue is also relatively stable from sampling to sampling, and the product has finer particles and is much more homogenous than the fish material. However, with a DM% of only 25-30 %, the moisture content will increase towards the bottom of a container with algae fibre, and this condition posed some challenge for calculation of the volumes of material to be applied in the field.

For two aliquot samples of algae fibre applied in the field study in 2019, total N concentrations were 1.24 and 1.28 % of DM. In 2020, the algae fibre had 1.8 % N. Average values from analyses of several batches of this material are shown in Table 4.

Table 4. Characteristics and chemical composition of materials applied in field experiments with marine-derived residual materials for fertilisation of agricultural crops 2019-2020. When more than one analysis has been performed, the number of analysed samples is shown in parenthesis.

Characteristic, (units)	Algae fibre low N	Algae fibre high N	Fresh fishbone	Acidified fishbone
DM (%)	22.3 (2)	25.5 (4)	27	48.5 (6)
pH (H_2O)	8.90	9.1 (6)	7.10	4.6 (15)
Tot N (% DM)	0.3 (2)	1.4 (6)	11	4.20
Tot C (% DM)	33.2	31.7 (6)	31	17.2 (12)
P (% DM)	0.4	0.3 (6)	6	10.3 (12)
K (% DM)	6.80	9.2 (4)	1.20	0.1 (10)
Ca (% DM)	8.40	5.4 (4)	11	13.9 (10)
Mg (% DM)	1.30	1.5 (4)	0.3	0.1 (10)
S (% DM)	1.30	1.2 (5)	0.6	0.4 (10)
Cl (% DM)	< 0.0003	1.3 (4)	1	1.4 (12)
As (mg/kg DM)	19	28 (5)	6.90	2.9 (12)
Cd (mg/kg DM)	0.9	1.0 (5)	0.02	0.13 (12)

3.4 Growth effects

3.4.1 Yields of oats and leek in outdoor pot experiment 2019

Despite that the applied amount of fertiliser was significantly lower than planned for the Fish and Mix treatments, these treatments gave the best dry matter yields (Figure 1). For oats, the production of aboveground plant material was much lower in the pots than in the adjacent plot experiment, but clear effects of fertilisation were revealed. The average number of plants per plot, after planting 30 seeds per pot, decreased from 29 at germination to 28 at harvest. There was no significant difference between treatments for the number of plants at harvest, or for the dry matter content of the aboveground plant material. The DM content was on average 24.4% and varied between 23.1% for Norg_L to 25.7% for Alg_H. The mean aboveground DM production of the oat plants varied between 4 g per pot for the Control and both mineral N (Nmin) treatments, to nearly 15 g for Mix_H with 70% of N from acidified fishbones and 30% from high N algae fibre, corresponding to 0.1-0.35 g DM m^{-2} (Figure 1). The treatments receiving fishbone fertiliser (Fish and Mix) had significantly higher yields than other treatments and the Control. A doubling of the fertilisation level did not give a significant yield increase in any treatment.

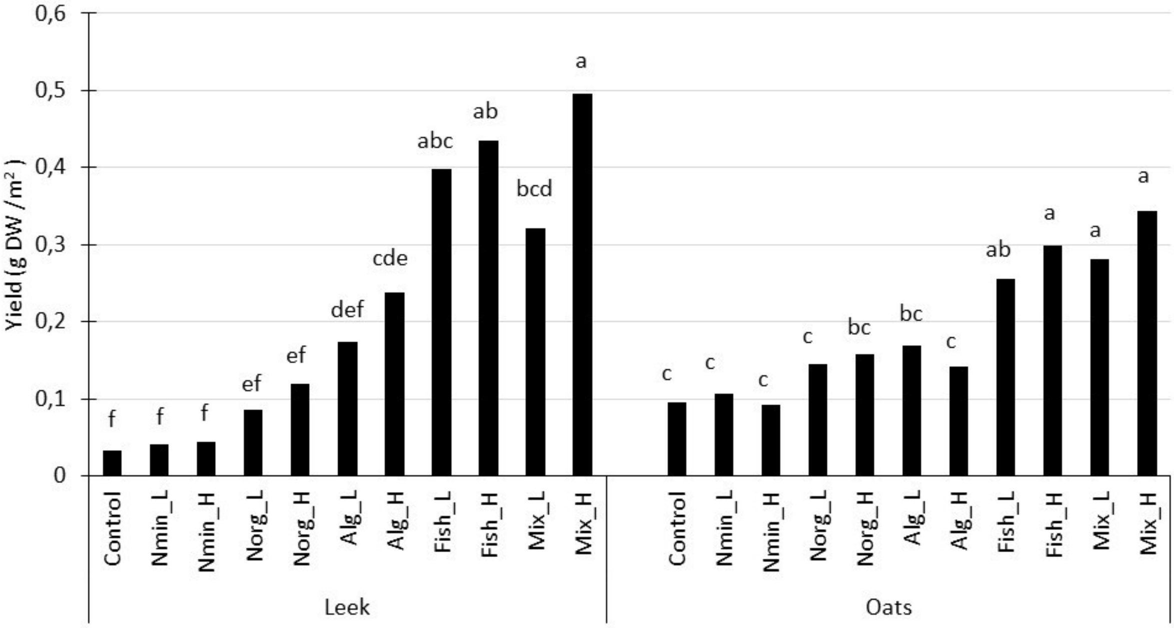


Figure 1. *Dry matter yields (g m^{-2}) in an outdoor field experiment with leek (3 plants per pot) and oats (28 plants per pot) fertilised with various materials in Low (L) and High (H) rates of total-N. For each crop, treatments assigned with different letters (a, b, ..) are significantly different at the 5% level. Norg= dried poultry manure with vinasse, Alg= algae fibre (residues from extraction of Ascophyllum), Fish = dried sediments from hydrolysed, acidified "white" fish (cod, saithe, etc.), Mix= 30 % of total N from Alg + 70% of total N from Fish.*

For the leek, the dry matter production per pot varied from about 0.2 to 0.5 g DM per pot, and the difference between treatments was higher than for the oat plants (Figure 1, Picture 9). Yields were very low for the Control and Nmin treatments, demonstrating that leek is a more nutrient demanding crop than oats. We could speculate that the irrigation at planting could have washed out the soluble mineral N fertiliser, but the oat pots were not irrigated, while the mineral N still gave very low yields of oat plants. The DM concentrations in leek plants was very low, about 11% for Alg_L and ALg_H, and highest for Fish_L, being 19.4%. Most treatments had DM contents between 16 and 18%.

Some positive effect on the growth of leek was obtained by poultry fertiliser (Norg), but the effect was smaller than for oat plants. The marine-derived materials performed much better in leek than in oats. In leek, if the Control yield is set to 1, the yields increased by a factor of 5-10 for algae, fish or mixed algae and fish, whereas in oats the yield increase was about 1.5 for algae and 2.5-3.5 for fish and mixed algae and fish. There was also a significant effect of fertiliser level (for Mix). This different pattern between the crops is likely due to the much longer growing period for the leek.

Picture 9. Pots with leek amended with different fertilisers, at harvest date September 3, 2019. All replicate pots in each treatment are shown, but the Control and Nmin_L treatments are not shown here. Order of treatments, from the left: Nmin_H, Norg_L, Norg_H, Fish_L, Fish_H, Alg_L, Alg_H, Mix_L, Mix_H. Photo by Ishita Ahuja.

With the soil volume in the pots being 8.6 litre, yields on an area basis may be computed as follows: Pot yield (g DM) / 8.6 dm^3 x 2 dm (topsoil depth) x 1 000 000 dm^2 = pot yield in g per soil volume of 1 hectare (ha). For conversion to kg DM ha^{-1} the number must be divided by 1000 (from g to kg).

The pot yields ranged from 924 kg DM ha^{-1} for Nmin_H to 3433 kg for Mix_H for oats. For leek, pot yields ranged from 323 kg DM ha^{-1} for the Control to 4954 kg for Mix_H. Fresh weight (FW) yields of leek varied from 0.2 tons ha^{-1} for the Control to 29.4 tons for Mix_H. The highest weight obtained per plant was 63 g, which is well below the required FW for commercial sale where one leek should weigh 200 g or more.

3.4.2 Yields of oats in field experiment 2019

In the field plots, the poultry manure gave better growth (Figure 2, left side). Norg increased oat yields by 38%. Algae fibre gave 9% lower yield than the Control. The mixing of algae material with fish waste (Mix) increased the yield by 74%, and fishbone material alone (Fish) by 60%. It is surprising that the yields were much better with application of fish material than poultry manure, since the N application was higher with Norg than Fish or Mix. The fertilisers were not very well incorporated since this was done by hand with a rake, and this may explain the poor effect of the poultry manure. The pH in poultry manure was 5.7, which is somewhat higher than in the acidified fishbones. Without any measures to control the weeds, the proportion of weeds in the canopy was high, especially in the Control, where the weeds comprised 61% of the canopy on a DM basis. The proportion of weeds was also high in Norg_H (56%). The clover plants from the recently established ley comprised only 1-2% of the canopy DM, which shows that the grass which could not be separated from the weeds most likely did not comprise any significant amount in this botanical fraction. The **algae material likely hampered the germination of some weed seeds**, because the proportion of weeds was only 35% in this treatment. It is interesting to note that the **algae fibre did not hamper the germination of clover seeds**, as the proportion of clover was not significantly lower in this treatment. Fish_H had 44% weeds, and Mix_H had 50% weeds in the canopy.

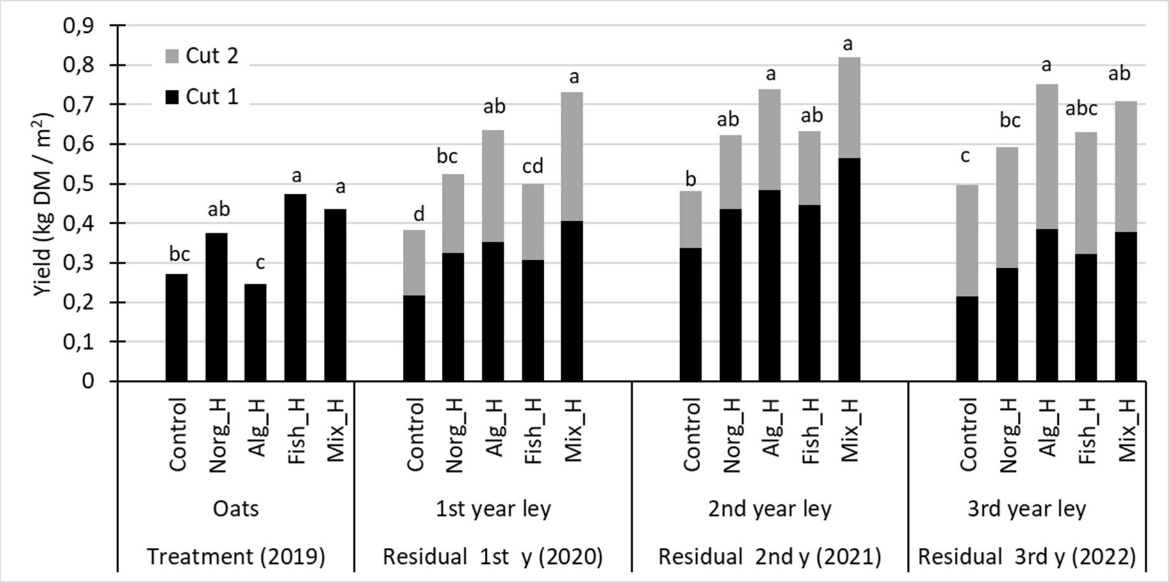


Figure 2. Dry matter yields (kg ha^{-1}) of oats harvested for green fodder on July 31, 2019, with ca. 160 kg total N ha^{-1} applied in various fertilisers in May 2019. Norg= dried poultry manure with vinasse, Alg= algae fibre (residues from extraction of Ascophyllum), Fish = dried sediments from hydrolysed, acidified "white" fish (cod, saithe, etc.), Mix= 30% of total N from Alg + 70% of total N from Fish.

The yields were much higher in the plot experiment than in the pot experiment. The pot yields of oats ranged from 0.092 to 0.343 kg DM m^{-2} (Figure 1) whereas the plot yields ranged from 0.24 to 0.48 kg DM m^{-2} (Figure 2). **We may conclude that the differences between fertiliser treatments may be clearly revealed in a pot experiment, but the yields are not so relevant for practical growing. Fishbone material gave significantly better yields than mineral N fertiliser and poultry manure, even if a smaller amount of N was applied with this material. Application of algae fibre may increase the plant growth for crops with a long period of nutrient uptake, such as leek.**

3.4.3 Ryegrass in field experiment 2020: Weeds by 1st cut

Annual weeds grew vigorously in the field experimental plots, with corn spurry (*Spergula arvensis* L.) as the dominating species. At the first cut, the proportion of weeds in the DM of the ryegrass canopy was significant. The botanical analysis showed that some of the fertilisers, when applied in the high rates which were used in this experiment, did reduce the proportion of weeds while giving a high yield (Figure 3). This was found for acidified fish material, including the Mix treatments, and this may possibly be explained by a high rate of ammonia being released. The algae fibre obviously also had a negative effect on the germination of weeds, as shown by the very low proportions of weeds found in Alg_L and both Mix plots. The high pH level may be one explanation for this. However, the early growth of ryegrass was also hampered by the high rate of algae fiber application in Alg_L, as shown by the very low yield level in this treatment at the 1st cut. Poultry manure and fresh fish (Frish_L) supported the growth of both ryegrass and weeds, but the N was obviously much more readily available from the acidified fish, since all treatments receiving that material had much higher yields than other treatments. The very high proportion of weeds in the non-fertilised Control demonstrates the importance of fertilising the crop plants for competition with weed growth.

At the 1st cut, the dry matter content was very similar for all treatments and varied from 13.0 (Alg_L) to 13.7 % (Frish_L). At later cuts, the DM content in Control and Alg_L remained around 13-14%, whereas in other treatments it was lower and varied between 10 and 12%.

We may conclude that high rates of fishbone material, and of algae fiber, may hamper the germination of seeds both from weeds and crop plants.

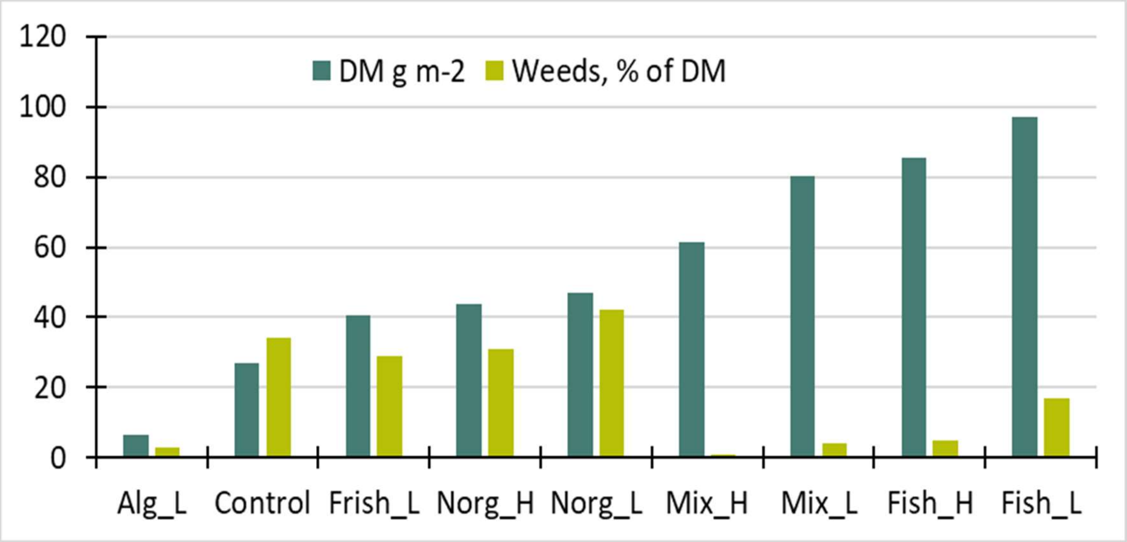


Figure 3. Dry matter yields of ryegrass canopy (g/m2, dark green columns) and weed proportions in the canopy (% of canopy DM, light green columns) at the 1st cut, June 30, 2020, arranged by increasing yield. Plots were amended with 300 (L) or 600 (H) kg total N ha^{-1} applied in various fertilisers in May 2020. Norg= dried poultry manure with vinasse, Alg= algae fibre, Fish = dried sediments from hydrolysed, acidified "white" fish, Frish = freshly grinded backbones of white fish, Mix= 30 % of total N from Alg + 70% of total N from Fish.

3.4.4 Yields of ryegrass in field experiment 2020

The yields of ryegrass increased significantly from the 1st cut to later cuts (Figure 4). The rates of applied fertilisers were much higher than were used for oats in 2019, but the growth response did not reflect this higher input. Similar to what was found for oats in 2019, Alg_L performed slightly poorer than the unfertilised Control, but towards the end of the season, algae fibre had a positive effect on plant growth. With better incorporation of the fertilisers in 2020, by hand-held rotovator, the poultry manure performed much better. Acidified fish fertiliser gave yields comparable with the same rates of N applied in poultry manure, whereas grinded fresh fishbones gave slightly lower yields. This may be due to a small initial growth effect, possibly caused by later mineralisation of N in this material (Figure 4). However, another reason may be a competition with other organisms for N, as discussed in Chapter 4.

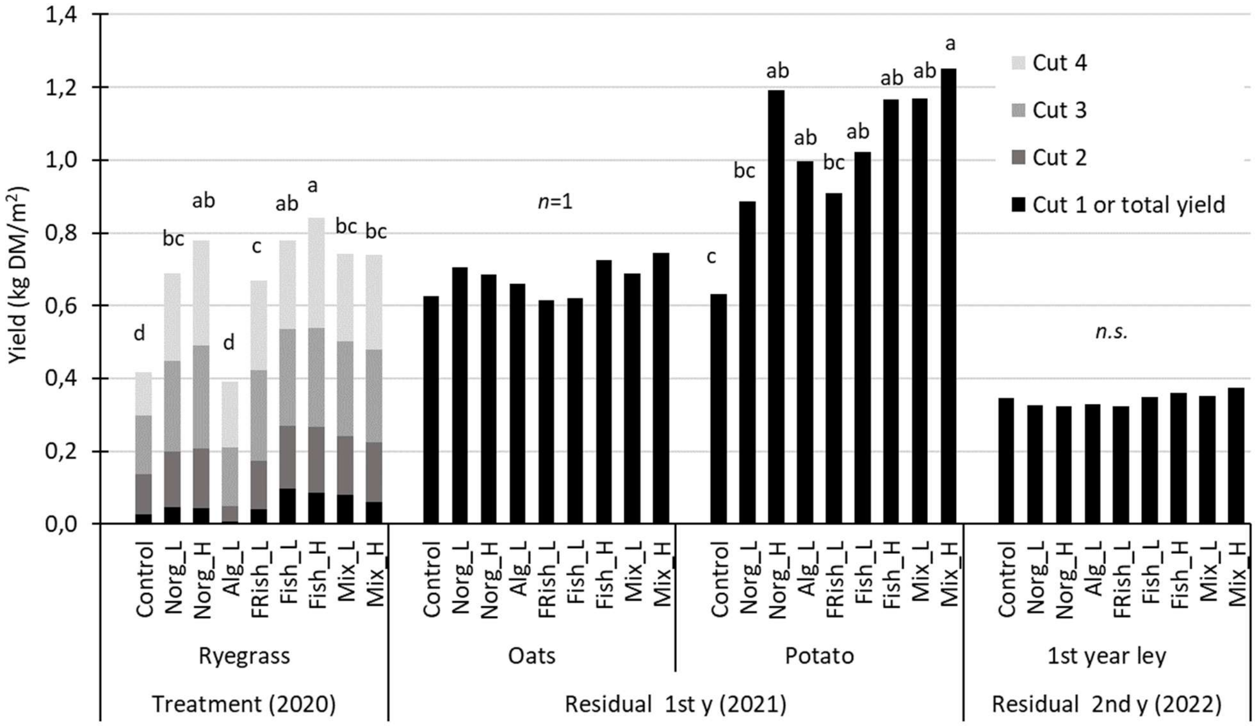


Figure 4. Dry matter yields (g/m^2, left side) of ryegrass in 2020 (4 cuts) and residual crops in 2021 and 2022. Plots were amended with 300 (L) or 600 (H) kg tot-N ha^{-1} applied in various fertilisers in May 2020. Norg= dried poultry manure with vinasse, Alg= algae fibre (residues from extraction of Ascophyllum), Fish = dried sediments from hydrolysed, acidified "white" fish (cod, saithe, etc.), Frish = freshly grinded backbones of white fish. Mix= 30 % of total N from Alg + 70% of total N from Fish.

We may conclude that with the conditions in the present study, a fertiliser rate above 300 kg tot-N ha^{-1} did not increase yield levels significantly. To achieve a good effect on plant growth, it is more important to incorporate poultry manure to a significant soil depth, than it is for fish material.

We further state that acidified fish material has a remarkable effect on early plant growth. This result is in line with what was found in the indoor pot experiment with ryegrass in 2018, even if that fishbone material was not acidified.

3.4.5 Residual effects of fertilisers on grass-clover ley, potatoes, and oats

For the experiment established in 2019, the growth of grass-clover ley during 2020-2022 was significantly affected by the 2019 fertilisation (Figure 2). The yields of the 1st cut in 2021 (2nd year ley) were remarkably high, in all treatments, which is likely due to the favourable weather conditions. Botanical analysis was not performed, but the red clover thrived in the plots that had received algae fibre (Mix and Alg). The long-term effect of the grinded fish sediments, which are very rich in bone material, was very similar to the residual effect of dried poultry manure with vinasse (Norg). The addition of a small amount of algae fibre to the fish material gave a highly significant yield increase, but algae material applied alone also increased ley yield significantly over several years. The accumulated dry matter production over 3 years (2020-2022) was 13.6 tons ha^{-1} for the Control, 17.4 for Norg_H (+28%), 17.6 for Fish_H (+29%), 21.3 for Alg_H (+57%) and 22.6 for Mix_H (66% yield increase).

The residual effects of fertilisers applied in 2020 for an annual crop of ryegrass were measured in 2021 with two experimental crops. For potatoes, we had three replicate plots, whereas for the oat crop, which was harvested for green fodder, there was only one replicate. The oat plants were harvested in late July after a short growing period, and hence did not utilise the residual nutrients as good as the potatoes did. Statistical analysis could not be performed, but the effects of fertilisers applied in 2020 were quite small (Figure 4). For potatoes, which were harvested in late August 2021, all fertilisers applied in 2020 increased the tuber yield, but for low rates of Norg and Frish, the differences were not statistically significant. The positive residual effect of algae fibre was highly significant for potatoes, as was found for perennial ley. For Fish and Mix, we found a positive, but not statistically significant effect of the fertiliser rate in 2020.

In late August 2022, no significant effects were found in the perennial ley which was established in May 2022. While the yields were not significantly different, there were differences in colour of the canopy in the late autumn, showing less green colour in Control and Alg_L plots.

We may conclude that algae fibre seems to have a remarkably strong positive effect on subsequent crops, despite of a low content of phosphorus. This may be due to a high content of other minerals, such as potassium, but may also be due to the organic material applied. For fishbones, the positive residual effect may be explained by the content of phosphorus as the nitrogen is most likely consumed in the first growing season after application.

3.5 Effects on soil characteristics and plant element concentrations

3.5.1 Soil pH and extractable nutrients

For the pot experiment, the fertilisers affected quite differently on the soil characteristics measured at the time of harvest (Appendix 4, Experiment 1). The effects were less significant in oats than in leek, likely due to the lower rates of fertiliser. From an initial pH level of 5.5 for soil applied for leek, and 5.7 for oats, algae fibre increased the soil pH at harvest to 6.3-6.4 (leek-oats) for the low applications, and 6.9-6.8 for high applications. In Mix treatments, the soil pH was 6.0-6.2 at harvest. For the remaining treatments and the Control, soil pH did not differ significantly at harvest. In the field experiment in 2019, soil characteristics after fertilisation were not measured until October 2020, but again, the algae fibre increased the soil pH significantly (Table 5).

Significant changes were also found for AL-extractable P, Mg and K (Appendix 4 Experiment 1; and Table 5). Fish material increased the soil P-AL concentration notably, from 24 to 100-200 mg P kg^{-1} air-dry soil in leek pots, and from 20 to 30-80 mg P kg^{-1} in pots with oat plants. In the field experiment, P-AL was higher in the unfertilised Control as well as in all fertilised treatments in October 2020 than in April 2019, possibly due to mineralisation of organic P during summer in this soil which is high inorganic matter. Significant differences in P-AL were found between the Control and the treatments, with the highest concentrations for fish material (Fish_H and Mix_H). For poultry manure (Norg_H), the P-AL concentration was not significantly different from the Control (Table 5). Algae fibre did not affect soil P-AL, but had a notable positive effect on Mg-AL and K-AL. In the pot experiment, the K-AL values increased from initially 43-49 (oats-leek) to about 200 and 400 mg K-AL kg^{-1} air-dry soil at harvest (Appendix 4, Experiment 1). Somewhat lower, but significant increases in Mg-AL were found for soil from the leek pots. In the field experiment, the increased concentrations of K and Mg-AL with algae fibre were still significant after 1.5 years (Table 5).

Table 5. Soil pH and nutrient concentrations in field experimental plots before application of marine residual materials as fertilisers in May 2019, and in October 2020. Oats were grown in 2019 and 1st year ley in 2020. Average values from four replicate plots per treatment. For each variable and sampling time, significantly different values ($p<0.05$) are assigned with different letters (a-c).

Treatment	pH		P-AL		Mg-AL		K-AL		Ca-AL	
					mg /kg dry soil					
	2019	*2020*	*2019*	*2020*	*2019*	*2020*	*2019*	*2020*	*2019*	*2020*
Control	5.73	5.55 b	23	39 c	45	42 b	40 b	32 b	855	415
Norg_H	5.73	5.55 b	24	48 bc	41	48 b	41 b	38 b	785	428
Alg_H	5.78	5.98 a	23	37 c	50	80 a	112 a	135 a	795	480
Fish_H	5.78	5.63 ab	33	80 a	45	44 b	39 b	30 b	897	470
Mix_H	5.73	5.70 ab	28	58 b	45	55 b	34 b	41 b	877	448

For the ryegrass experiment in 2020, the topsoil was sampled and analysed per plot in spring and autumn of 2020. In spring, there were no statistically significant differences between treatments for soil pH or AL-extractable nutrients (Appendix 4, Experiment 3; Table 6). In autumn, soil pH had increased from initially 5.5 to 7.2 with the low rate of N applied as algae fibre (Alg_L), and to 6.1 and 6.5 with Mix_L and Mix_H. Other fertilisers did not affect the soil pH, which varied between 5.3 and 5.6 for the Control, Frish, Fish, and Norg treatments. This pattern is quite similar to what was found for the experiments conducted or initiated in 2019. For extractable nutrients, trends were also comparable with previous results. Except for the Fish and Mix treatments, the soil P-AL concentration on the ryegrass experimental plots was lower in the autumn than in the spring of 2020 (Table 6), showing the capacity of the soil to deliver P to the plants and the capacity of ryegrass plants to take up P.

Table 6. Soil pH and nutrient concentrations in spring and autumn of 2020, before and after application of marine residual materials as fertilisers and growing a ryegrass crop which was cut four times. Average values from four replicate plots per treatment. For each variable and sampling time, significantly different values (p<0.05) are assigned with different letters (a-d). Within each treatment, statistically significant changes from spring to autumn are indicated by a grey shadowing of the result obtained in autumn.

	pH		P-AL		Mg-AL		K-AL		Ca-AL	
					mg kg^{-1} dry soil					
Spring 2020										
Control	5,5		37,5		55,3		145,0		400,0	
Norg_L	5,5		38,5		58,0		146,8		425,0	
Norg_H	5,4		42,0		59,5		140,0		435,0	
Alg_L	5,5		39,8		58,5		130,0		447,5	
FRish_L	5,4		39,0		55,8		152,5		430,0	
Fish_L	5,4		39,8		59,3		137,5		450,0	
Fish_H	5,5		43,3		60,0		162,5		440,0	
Mix_L	5,5		42,8		52,3		146,3		387,5	
Mix_H	5,4		41,3		54,0		145,0		442,5	
Autumn 2020										
Control	5,5	d	26,3	d	37,8	d	80,3	b	265,0	d
Norg_L	5,5	d	32,5	d	28,3	d	76,8	b	230,0	d
Norg_H	5,3	d	36,8	cd	30,0	d	89,8	b	245,0	d
Alg_L	7,2	a	22,5	d	175,0	a	260,0	a	537,5	a
FRish_L	5,4	d	30,3	d	32,3	d	58,5	b	252,5	d
Fish_L	5,5	d	77,8	b	31,0	d	56,0	b	315,0	cd
Fish_H	5,6	d	118,0	a	27,8	cd	53,3	b	367,5	bc
Mix_L	6,1	c	56,3	bcd	50,8	c	76,0	b	360,0	bc
Mix_H	6,5	b	74,0	bc	74,3	b	104,8	b	440,0	b

Even the highest application of poultry manure did not increase soil P-AL. Whereas the fresh backbones of white fish did not increase soil P-AL, the acidified fish had a high and positive effect. This indicates that acidification by formic acid may make the P in the fishbones more available for plant uptake (Picture 10). The result is contrary to the results obtained by a study in the laboratory (Løes et al., 2022b). It is possible that in the laboratory study, dissolved phosphate was precipitated by dissolved calcium, as the fishbones contain significant amounts of calcium. The soil concentrations of extractable calcium were also lower in autumn, and the decrease was statistically significant for the Control and Norg treatments (Table 6). The increased Ca-AL from spring to autumn with algae fibre was not significant, but the Ca-AL concentration was highest in this treatment in autumn, with 538 mg Ca kg^{-1} air-dry soil. Treatments with acidified fishbone (Fish_H, Max_L and Max_H) also had higher Ca-AL concentrations in autumn than Control, Norg and Frish treatments, indicating that the acidification also increased the bioavailability of Ca. However, in the plant material, concentrations of P and Ca were not generally higher in ryegrass amended with acidified fish than non-acidified fish (Appendix 1, Experiment 3).

Picture 10. Bones from heads of cod (Gadus morhua) contain high amounts of P and Ca. Acidification by formic acid seems to increase the bioavailability of these plant nutrients. Photo: Anne-Kristin Løes.

Ryegrass takes up significant amounts of K, Mg and Ca, as shown by the generally decreased concentrations of these nutrients from spring to autumn. Algae fibre increased the concentrations of K-AL and Mg-AL significantly, from 130 to 260 mg K, and from 59 to 175 mg of Mg kg^{-1} air-dry soil (Table 6).

We may conclude that algae fibre increases soil pH and concentrations of AL-extractable K and Mg, while acidified fish residues increase soil concentration of P-AL and Ca-AL. Residues of fresh fish do not affect soil P-AL in a short-time perspective (within one year).

3.5.2 Effects of fertilisation on soil concentrations of potentially toxic elements

The concentrations of cadmium (Cd), arsenic (As), mercury (Hg) and zinc (Zn) are of special interest, because the concentrations of these elements decided whether the materials that were applied in our studies were classified as Class 0-III soil amendments (see section 3.5.4). In Appendix 3, soil concentrations of potentially toxic elements (PTEs) are presented. In the pot experiment in 2019 (Experiment 1), the applications of marine materials did not seem to affect the soil concentrations of any PTE. However, the limit of quantification (LOQ) for As was quite high at the laboratory (Eurofins), being 2 mg kg^{-1} dry soil. Later analyses were conducted at Nemko Norlab, with a lower LOQ; 0.37 mg kg^{-1} dry soil (Table 7). In the algae fiber treatments, which received the highest amounts of As, about 0.10 and 0.20 mg As kg^{-1} dry soil was applied for oats in Alg_L and Alg_H in pots in 2019. For leek, the amounts were double as high, 0.20 and 0.40 mg As kg^{-1} dry soil. To identify effects of such low applications on soil concentrations, the reporting limits (LOQ) must be very low. Upon request, we received values from Nemko Norlab below the LOQ. Such values have been presented in this report, even if they are not accredited, because we wanted to see if we could trace concentrations especially of As, Cd and Hg.

Table 7. Limits of quantification (LOQ) and detection (LOD), and measurement uncertainty level (%) for 19 elements where Nemko Norlab (Namsos, Norway) is accredited for analysis total element concentrations.

Element	LOQ	LOD=0,3xLOQ	Unit	Uncertainty (+/-), %
K	29	8.7	mg/kg TS	20
Mg	21	6.3	mg/kg TS	25
Ca	220	66	mg/kg TS	15
Cr	280	84	µg/kg TS	20
Mo	170	51	µg/kg TS	30
Mn	56	16.8	µg/kg TS	20
Fe	3800	1140	µg/kg TS	20
Co	13	3.9	µg/kg TS	20
Ni	80	24	µg/kg TS	30
Cu	520	156	µg/kg TS	30
Ag	85	25.5	µg/kg TS	15
Zn	150	45	µg/kg TS	20
Cd	1.4	0.42	µg/kg TS	25
Hg	700	210	µg/kg TS	20
Sn	3800	1140	µg/kg TS	30
Pb	60	18	µg/kg TS	30
As	370	111	µg/kg TS	25
P	32	9.6	mg/kg TS	25
S	1200	360	mg/kg TS	20

In the plot experiment with oats in 2019 followed by perennial ley (Experiment 2), soil sampled before fertilisation was analysed by Eurofins, with high LOQ value for As, whereas samples from 2020 were analysed by Nemko Norlab with lower LOQ. We could then see that application of algae fibre had increased the concentration of both As and Cd in the soil as compared with the Control soil (Annex 3, Experiment 2). Analysis of AL-extractable As showed the same trend. For Hg, the LOQ was higher at Nemo Norlab than at Eurofins so no trends could be seen here. The concentrations of Zn were high as compared with other PTEs and no effect of fertilisation could be seen.

In the plot experiment with ryegrass in 2020 (Experiment 3), soil sampled before fertilisation and after the final harvest was analysed by Nemo Norlab. In general, soil concentrations of As decreased from spring to autumn, but application of algae fiber increased soil As, especially in the treatment Alg_L where about 10 tons of algae fibre DM per hectare was applied (see Section 3.5.4). Here, the average concentration of As in the topsoil was increased by about 50%, from 0.85 to 1.28 mg kg^{-1} dry soil (Appendix 3, Experiment 3). The concentration of Cd increased from 0.06 to 0.07 mg kg^{-1} dry soil. With 1 kg DM of algae fibre per m^2, about 28 mg As is applied per m^2 (Table 4), corresponding to 28 mg/200 dm^3 = 0.14 mg As per litre of topsoil (0-20 cm). The measured increase was even higher than this, but an exact correspondence here cannot be expected. The increase may indicate that the As was attached to soil oxides, since arsenic behaves quite similar to phosphorus in the soil, and was not leached from the soil during the first growing season after application of algae fiber in the field. It is also interesting to see whether ryegrass or other plant material fertilised with algae fiber had higher concentrations of arsenic or other PTEs, and we will get back to that question in section 3.5.6. We first, however, need to clarify the amounts of fertiliser materials which were applied according to Norwegian regulations, to prepare for the presentation of results of element concentrations in plant material. Were the applied amounts realistic for amounts which Norwegian farmers might apply in practice, while keeping in line with relevant regulations?

3.5.3 Amounts of materials per unit area: fertiliser or soil amendment?

The chemical composition of the fish and seaweed residues applied in the studies presented here, was not well balanced to cover the need of crop plants for nutrients when the materials were applied alone. When algae fiber was applied to cover crop plant's need for nitrogen, the application of other nutrients such as K was extremely high. For ruminants, imbalances in the ratios between various cations and anions in the feed can cause significant health issues, even leading to sudden death. Hence, the plant material produced in the field experiments in the year of applying marine-derived fertilisers was not used as feed but taken away for composting.

In the future, the studied materials may be applied as ingredients in compound organic or organic-mineral fertilisers, where the applications will be adapted to crop needs. However, this future is not necessarily very near, and meanwhile, application of these materials as soil amendments may be relevant for the farms that are located nearby marine industries. For application as soil amendment, the amounts per hectare is decided by the availability of materials, cost of transport and regulations of potentially toxic elements. While the Norwegian regulation (Lovdata 2022, § 27) states that "*applied amounts should not exceed the nutritional demand for agricultural crops*", it does not specify for which nutrient this should be regulated. The largest negative effects on the environment will arise from applying excess N or P. Norwegian soils usually have a high capacity for storage of P, and hence we may put an application of 300 kg total N per hectare as a maximum application, while controlling that this amount does not exceed the limits for potentially toxic elements (PTEs).

In section 3.5.4, the fertiliser materials applied in the present study are categorized into soil amendment classes. In section 3.5.5, we have presented some plant concentrations of K, Mg and Ca as tetany ratios, essential for animal health. In section 3.5.6, we have presented data for concentrations of As and Cd in plant material. Plant nutrient concentrations may also be used to calculate nutrient uptake, nutrient efficiencies, and nutrient balances; however, such approaches are outside the scope of the present report.

3.5.4 Soil amendment class of fertiliser materials by PTEs

Arsenic was proposed to be included as a new PTE (in addition to Cd, Cr, Cu, Hg, Ni, Pb, Zn) in a proposal for new Norwegian regulations on organic fertilisers, published in 2018 (Norwegian Agriculture Agency, 2021). **The proposed thresholds for As** (Class 0 : < 5, Class I : < 8; Class II : < 16; Class III : < 32 mg As kg^{-1} DM) **would significantly hamper the use of materials from brown macroalgae for fertilisation**, especially because the regulation would not permit the "dilution" of materials exceeding 32 mg As kg^{-1} DM by other materials. Materials in Class III are not permitted on agricultural soil and can only be applied as a cover for waste deposits etc. For materials in Class II, up to 20 tons of DM may be applied per hectare over 10 years. For Class I, up to 40 tons may be applied, and for Class 0, the limit is decided by the nutrient content, which should not exceed the plants' demand.

The average value of As in algae fiber in our study was 28 mg kg^{-1} DM (Table 4), and for five samples this value varied between 27 and 33 (Zikeli et al., 2022). This would put algae fiber in Class III (not permitted for use on agricultural soil). Meanwhile, with the existing regulation, the concentration of cadmium in seaweeds is the limiting factor for algae fiber. For five samples that were analysed, all had > 0.8 mg Cd kg^{-1} DM (variation 0.9-1.1 mg); hence this material is Class II. For other PTEs, algae fiber is Class 0 for Cr, Cu, Ni, Pb, and Zn. For Hg, one sample had 0.8 mg kg^{-1} DM, which is Class II, but on average the value was Class 0 with 0.044 mg (Zikeli et al., 2022).

For fish residues, analyses of acidified fishbones, presented in Zikeli et al. (2022), show that this material was Class 0 for Cd, Cr, Cu, Ni and Pb in all cases (12 analyses). For mercury (Hg), the material was on average in Class I with 0.23 mg kg^{-1} DM, with some samples in Class II; the maximum value found was 0.7 mg kg^{-1}. For zinc (Zn), the material was Class 0 but close to Class I (limit 150 mg kg^{-1} DM), with an average value of 125 and the maximal sample having a value of 180. For As, if the proposed regulation is implemented, the material would be in Class 0 with an average value of 2.86 mg kg^{-1} DM. However, the maximal recorded value of 7.1 mg As kg^{-1} DM would put this material in Class I, demonstrating that analyses are required for a safe management of materials as soil amendments.

For PTEs in fresh fishbones, we have conducted less analyses, but for two samples, the concentration of As was slightly above the proposed Class I limit with 5.1 and 5.2 mg kg^{-1} DM, and for one sample the concentration of Hg was above Class I limit with 0.34 mg kg^{-1} DM. For all other elements, the material was in Class 0.

We may conclude that with **algae fibre will be a Class II soil amendment due to the content of Cd** and may be applied an amount corresponding to maximum 20 tons of DM per hectare over 10 years. If the material has 25% DM, amounts up to 80 tons per hectare (= 8 kg per m^2, corresponding to 2 kg DM per m^2) may be permitted. In the experiments presented here, the highest amount of algae fiber corresponded to 8.1 kg of material (with about 25% DM) per m^2 in the pot experiment with leek in 2019. For ryegrass in 2020, up to 7 kg material m^{-2} was applied, corresponding to 1.75 kg DM m^{-2}, and for oats in 2019 the amount was 4 kg m^{-2}, corresponding to 1 kg DM m^{-2}. The maximum application rates, in leek pots and ryegrass with low rate of algae fibre, were close to the limit of 20 tons of DM per hectare over 10 years. This amount restricted the germination of seeds, increased soil pH to about 7, and increased soil As by about 50%. **An application of half of this amount each 5th year would likely have been better for soil health and crop growth.**

For fish residues rich in bone material, As, Hg and Zn are the elements which need to be considered for application as soil amendment. **The material may be Class I due to Hg** and should not be applied with more than 40 tons of DM per hectare over 10 years. With 50% DM, maximum 80 tons per hectare could be applied over 10 years. An application of 300 kg of total N per hectare and year will cover the need for N for most crop plants, and higher amounts should never be applied. If we start out by a modest value of 4 % total N (% of DM) as it was found in the present studies after storage, 15 tons per hectare of fishbone (= 7.5 tons of DM) will provide 300 kg N, and this could be applied every 3-4 years to keep the limitation according to the Class I regulation. However, with the high content of P (6-10% of DM, Table 4) this amount of fish material will provide 450-750 kg P of per hectare, which is a very high rate of P fertilisation. If we could conserve the N in the fish material to achieve 11% total N (% of DM), we would only need about 5.5 tons of material (2.7 tons of DM) per hectare to apply 300 kg per hectare of N, and that would imply a P fertilisation of 160-270 kg per hectare. This is still a high rate of P fertilisation, and fish materials should only be applied as a soil amendment where the soil is low in P and would benefit from increased P-AL levels. It will be a challenge to spread such a low amount of material as 5.5 tons per hectare evenly in the field, unless the material is pelleted, diluted, or blended with other materials.

We may conclude that the high rates of material applied in the present study in 2019, and the low rates applied in 2020, are representative for amounts that may be permitted in practice if such materials were applied as soil amendments according to limits given in the Norwegian regulations for organic fertilisers and soil amendments.

Hence, we can proceed to assess how the applied amounts affected the concentrations of elements in the plant material. We need such assessments before we may conclude that the amounts that may be applied on an area basis according to the content of PTEs are also safe with respect to crop quality.

3.5.5 Plant concentrations of nutrients: tetany ratios

In all treatments of the field experiment with oats in 2019, the concentration of K was high compared with Ca and Mg (Figure 5).

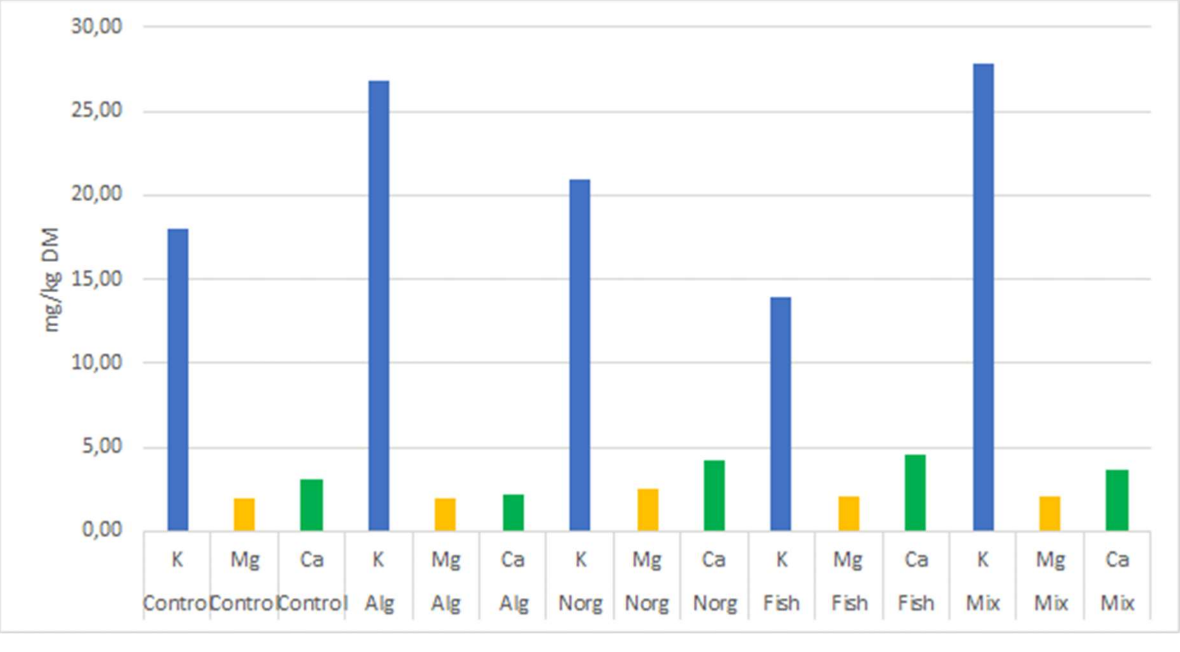


Figure 5. Concentrations of K, Ca and Mg in aboveground material of oat plants, harvested as green fodder at late flowering in 2019, mg/kg DM. For each fertiliser treatment, blue columns show concentrations of K, yellow columns show concentrations of Mg, and green columns show concentrations of Ca.

However, oats amended with algae fiber had higher concentrations of K than oats fertilized by other materials, both in the Mix and Alg treatments (Figure 5), while the concentrations of Ca and Mg were lower especially where only algae fiber was applied. To assess the risk of tetany in ruminants (sudden death due to cation imbalance, commonly caused by intake of feed rich in K), the ratio between K over (Ca+ Mg) in milliequivalents may be computed (Manitoba Agriculture 2004). The concentration of K is then multiplied by 256, Ca by 499 and Mg by 823, before computing the ratio. **To avoid tetany, the ratio should be < 2.2.** For the oat plant material in 2019, the ratio was 2.53 for algae fiber, 2.02 for the Mixed treatment (30% of N from algae fiber), 1.5 for the unfertilised Control, 1.3 for Norg (poultry manure) and 0.9 for the Fish. This shows that it was indeed reasonable not to apply the oats from the algae fiber treatment as feed. We did not analyse plant material from the 1st year ley in 2020, but for the 2nd year ley, the ratio had decreased to 1.47 at the 1st cut and 1.23 at the 2nd cut in plots which were amended with algae fiber in 2019. The concentrations of K, Ca, Mg, and other macronutrients are shown in Appendix 1, Experiment 2.

For the canopy of oats in 2021, grown the year after application of marine fertiliser materials, the tetany ratios were high in all treatments, because this crop (along with the potatoes) had received a dressing of 120 kg N ha^{-1} with poultry manure "Grønn Øko 8-3-5" (enriched with vinasse). This implied a K fertilization of 75 kg ha^{-1} in 2021. Tetany ratios ranged from 1.4 in Fish_H to 2.5 in Alg_L, demonstrating that algae fiber may affect the tetany ratio also in subsequent crops. Results are shown in Appendix 1, Experiment 3.

For ryegrass in 2020, with very high fertiliser applications of 300 and 600 kg tot-N ha^{-1}, the tetany ratios for cut 1-4 varied between 1.4 and 4.0. On average across all treatments, the ratio increased from 2.2 at the 1st cut, over 2.8 to 2.6 and 2.4. The highest levels were reached for Norg_H and Norg_L. With algae fibre, the ratio was relatively low at cut 1 and 2, and then increased (Figure 6).

These results, especially for the high fertilisation rates in 2020 which are not relevant for practical agriculture show that **very high rates of fertilisers may induce risk of tetany in fodder crops even for well-balanced fertilisers such as poultry manure**. Hence, **fertilisation must be adapted to the crop nutrient demand to avoid excess uptake of nutrients which may cause negative effects on animal health when the crop is applied for feed.** It further shows that **the tetany ratio seems to decrease to a safe level while the yield effect of the algae fiber still pertains, when algae fiber is applied in an amount of about 10 tons of DM ha^{-1}.** There is a need for more knowledge about how the farmers can cope with this issue in a practical farming system.

A complete overview of the concentrations of macronutrients and other elements in plant material is shown in Appendix 1, Experiment 1, 2 and 3.

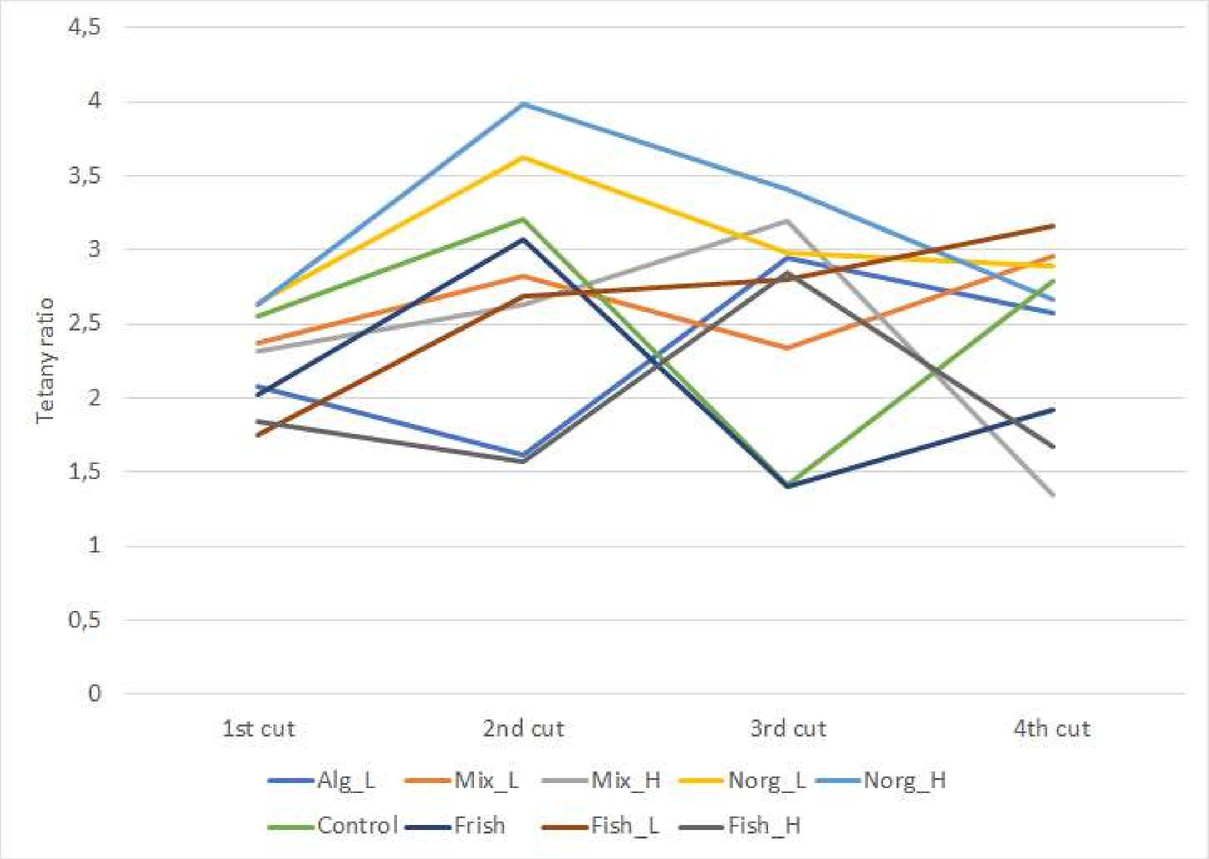


Figure 6. Tetany ratio (mEq K/(mEq Mg + mEqCa)) in ryegrass at cut 1-4 with different fertilisation, field plot experiment 2020.

3.5.6 Plant concentrations of PTEs

In Appendix 2, concentrations of potentially toxic elements As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn are presented. Of special interest for fertilisation with marine materials are As and Cd for algae material, and Hg for fish material. Zn also is of interest, since the concentrations are often high of this element, which is also an important plant nutrient (see section 3.5.4). The reporting limit (= limit of quantification, LOQ) for plant analyses of As at Actlabs was 0.5 mg As kg^{-1} DM, and at Nemko Norlab it was 0.37 mg. All plant samples were below the limit of Actlabs in the pot experiment with leek and oats in 2019 (Experiment 1) and below the Actlab and Nemko limits in the field plot experiment with oats in 2019, followed by ley sampled in 2021 (Experiment 2). For Hg, all analyses were also below reporting limits (Appendix 2 Experiment 2). For Cd, the concentrations were above the limits, but did not increase with application of algae fiber. For Zn, the concentrations tended to be highest in the Control samples and were not increased by application of marine materials.

For the ryegrass in 2020 (Figure 7), the As concentrations in the aboveground plant material were generally highest at the 1st cut and then decreased to very low values, with some few exceptions. Except for one high value for the low rate of Fish, the concentrations were not higher in plant material amended with marine materials than in plant material fertilised by poultry manure. The results in Figure 7, as well as the results for As and some other elements in Appendix 2 Experiment 3 are reported also when they are below the limit of quantification, to see if we could find any indications of increased uptake of As, Cd or Hg in plants amended with algae fiber or other marine materials.

The concentrations of Hg were always below the LOQ, and we found no indications of higher concentrations of As or Cd in plant materials after amending the soil with marine materials.

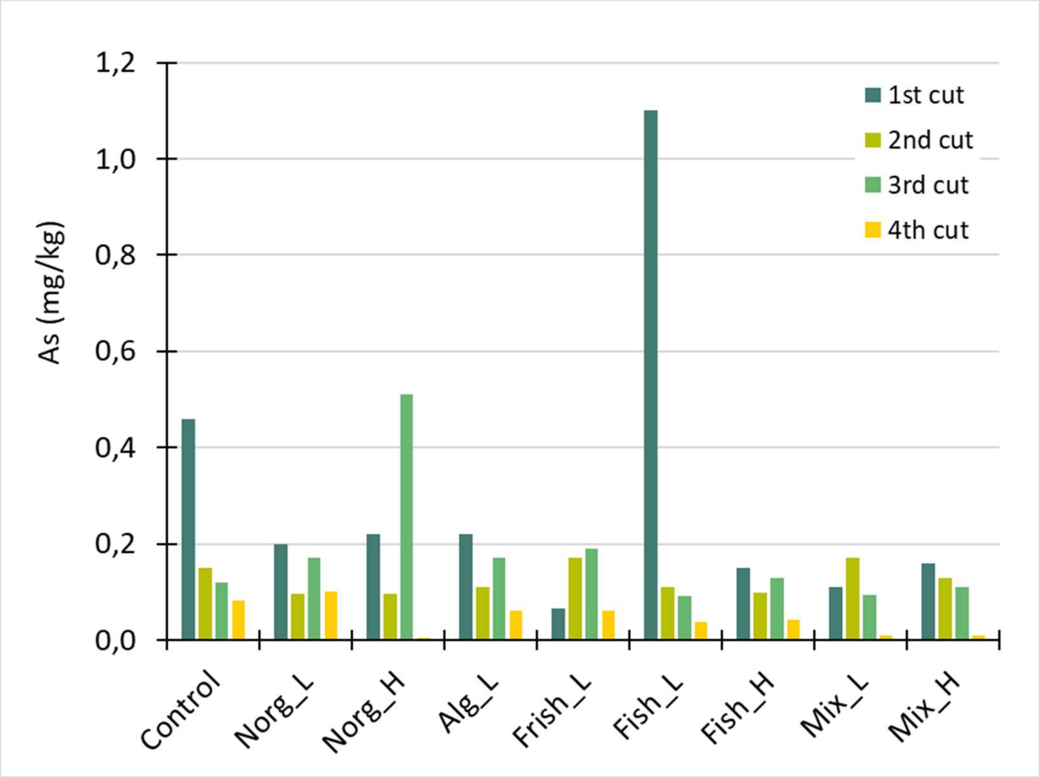


Figure 7. Concentrations of arsenic (As), mg kg^{-1} DM in ryegrass cut at four dates in the growing season of 2020. Plots were amended with 300 (L) or 600 (H) kg tot-N ha^{-1} applied in various fertilisers in May 2020. Norg= dried poultry manure with vinasse, Alg= algae fibre (residues from extraction of Ascophyllum), Fish = dried sediments from hydrolysed, acidified "white" fish (cod, saithe, etc.), Frish = freshly grinded backbones of white fish.

4 Decomposition of fertiliser materials in net bags, 2020: methods and results

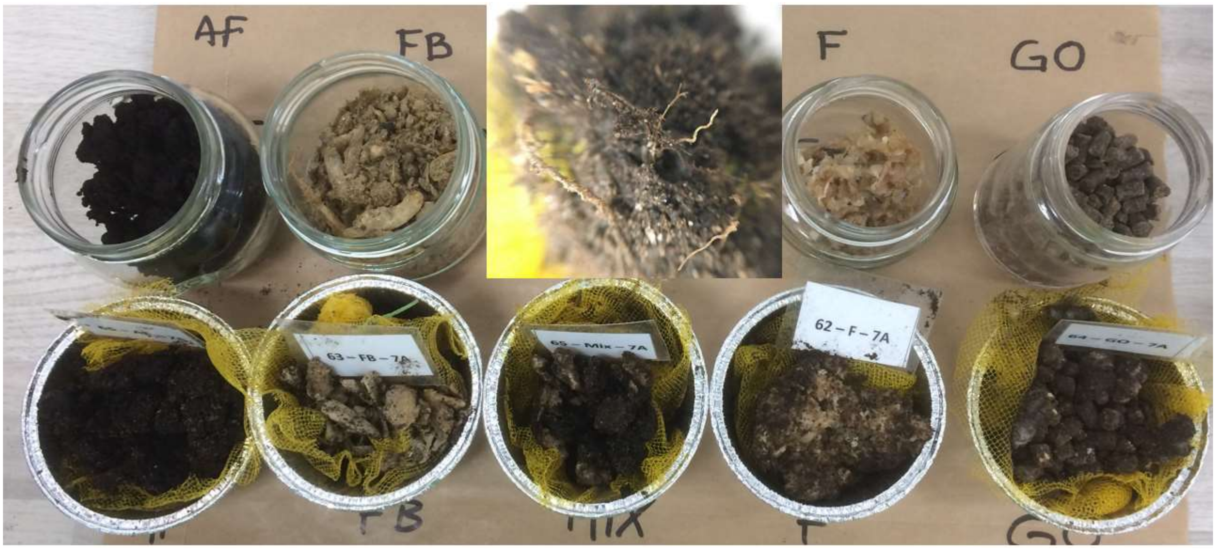
Small batches of the materials that were applied as fertilisers for ryegrass in the field experiment in 2020 were put in net bags (Picture 11 and 12) and buried in soil at 15 cm depth on a plot adjacent to the ryegrass field experiment (Picture 11). Each bag contained 20 g of fresh fish material, or 30 g of other materials. Seven shallow pits were dug out in tilled soil. Each pit contained two bags of each fertiliser type (algae fibre (AF), fresh grinded fish material (F), acidified grinded fish material (FB), mix of acidified fish material and algae fibre (Mix), and dry poultry manure commercial name “Green Organic” (GO), arranged in random order. Bags were covered with soil and the surface flattened by hand before planting of ryegrass seeds. The distance between bags was about 5 cm, and the distance between pits was 0.5 m. At seven sampling dates (June 11, June 18, July 2, July 16, August 17, September 14, and October 14, 2020), one pit was “harvested”. The bags were weighed, the content was studied by visual observations, and the odour of the bags observed and described. For comparison at each sampling date, the materials in their original state (Picture 13), except for the Mix, were stored at 4 °C in glass containers. To identify the materials, a label with a material code (Picture 11) was put inside the net bag, and this label was used as a basis for placing the materials and located on the bottom of the bags.

Picture 11. Net bags with algae fibre or other materials applied as fertilisers were buried in soil adjacent to the experimental ryegrass field on June 4, 2020, and regularly “harvested” for visual study of material decomposition. Photos by Anne-Kristin Løes.

After one week (first sampling, June 11), the odour was less intense than we expected. As long the materials were kept inside the closed net bags, it was not easy to differentiate between the materials by odour. More soil was attached to the net bags containing fresh fish than for other materials, and the soil attached to bags containing F and GO was more strongly attached to the bags than to bags containing AF, FB, or Mix. Mould was observed on the GO pellets, and in the soil surrounding the GO bags. For all materials, thin, brownish “roots” were observed which were entering the net bags (Picture 13).

Picture 12. Fertiliser materials for decomposition study in soil. From left, algae fibre, acidified fish material mixed with algae fibre, acidified fish material, dried poultry manure and fresh grinded fish material. Photo by Anne-Kristin Løes.

These “roots” could not be identified as roots from living plants, since hardly any plants had started to grow on the plot where net bags were buried after only one week. Several individuals of rove beetles (Staphylinidae) were observed in the net bags containing F material, as well as in the soil attached to these bags. The F material was glued together as a solid “cake”, and no animals were observed inside this. When the net bags were opened, the odour from the materials was more evident. The smell from F was likely due to ammonia and was sharper than for F which had been kept cool. For GO, the odour was still clearly poultry manure, but with a pleasant note for the material which had been buried in soil, reminding of a cow’s skin by sunshine.



Picture 13. Back row: Glass containers with fertiliser materials that were kept cool. Front row: The same materials after 1 week in soil in net bags. In the middle of back row: Close-up of soil attached to a net bag, with many thin “roots” entering the material inside. Photos by Anne-Kristin Løes, June 11, 2020.

After two weeks (June 18), there was significant mould on the FB material. The odour of fish had disappeared, even when a piece of bone was broken, no odour could be noticed. Inside the AF bags, the characteristic odour of algae fibre was still significant, even if it was not as strong as observed in the fresh material. This odour was strong and composed of seaweeds with a distinct chemical note. For poultry manure, the bags were "stuffed", likely because the material had attracted water and swelled. A thick layer of mould had developed outside the net bags and between GO pellets. For the Mix, white hyphae were visible in the algae fibre, and the whole material stuck together like a "cake". The fish material (F) was more wet and decomposed than on June 11, and the odour was surprisingly weak as compared with the appearance of the material.

After four weeks (July 2), there was still significant mould on the FB. Soil was attached to the surface of fishbone pieces, which had developed a pink-brownish colour (Picture 14). No animals were observed in the FB bags. The smell reminded of a basement with storage of potatoes. The AF and the Mix bags were "leaching" some black liquid which sticked to the fingers while harvesting the bags. On the algae fibre, small light brown spots had developed on the surface (Picture 14). Inside, there was a white mould. The characteristic odour had disappeared, also when clumps of the material was broken. The smell now reminded of wet peat soil. Inside the Mix bags, several animals were identified, such as mites, beetles, larvae with feet, and collembola. The odour was simply "soil". Inside the GO bags, there were many flee larvae, small and large (Picture 15), and the odour was sharp, likely caused by ammonia. Poultry manure is sanitised at a high temperature before packing, and the infecting of the pellets with fly eggs or larvae most likely occurred while the bags were buried in soil. The F material was very decomposed, with visible pieces of fish bones surrounded by clumps of fishbone covered by soil. A rove beetle was found in one F net bag.

Picture 14. Algae fibre (AF) after three weeks of "storage" in soil; light brown spots had developed on the surface of the fibre. In acidified fishbones (FB), there was a lot of mould, and soil was attached to the bone surface. Photo by Anne-Kristin Løes, July 2, 2020.

Picture 15. Decomposing poultry manure with fly larvae. Photo by Anne-Kristin Løes, July 2, 2020.

After six weeks (July 16), the ryegrass was about 30 cm high, and ryegrass roots grew into the top and bottom parts of the net bags. Inside an AF and a Mix net bag, earthworms were found. The soil attached to the bags, which until now had to be removed by help of a piece of metal for scraping on some materials, was now quite loose and could be removed by hand. For most materials, the appearance had not changed very much since he previous sampling, but for the F material, only bone particles were now left (Picture 16) and the odour was like a basement where potatoes are stored. The F material which had been kept cold and closed, was decomposing into a dry part with mould on top and a liquid in the bottom of the glass (Picture 16), with a sharp odour from ammonia, but no fish odour anymore. Inside GO net bags, the odour was still somewhat sharp from ammonia, but the smell of poultry had disappeared. Some larvae were found in the decomposing manure (not from flies).

After 11 weeks (August 17), plant roots grew vigorously into the net bags, especially when filled with GO, FB, and Mix. Roots were observed to grow into fishbone pieces. Some animals were found; one enchytraidae (roundworm) in AF, earthworms and enchytraidae in GO, one yellow larva and one beetle in Mix, collembola in F. The odour of GO was now like garden soil; in other materials the odour was weak. The mould was much less significant than at earlier dates. After 15 and 19 weeks (September 14, October 14), the root growth into all bags was extensive, and several roots were surprisingly coarse. A smooth knife was applied to remove the surface soil from the bags. In September, the occurrence of animals was similar to what was found in August, with several earthworms and enchytraidae. Some insect pupae were found in F. Remaining pieces of acidified fishbone were quite soft and could easily be penetrated by the tip of a thin metal piece, whereas fresh fishbones were harder. In October, less animals were found, but some collembola in GO. Some of the original material could still be revealed inside all the bags (Picture 17), but the amount was much smaller than was buried in June, especially for AF and F.

Picture 16. Net bags with material of fresh fish backbones after four weeks of decomposition in soil, compared with the same material stored at 4 °C in a glass container. Photo by Anne-Kristin Løes, July 18, 2020.

Picture 17. Remains of material buried in soil over 19 weeks (June-October 2020), from above alga fibre (AF, left), algae fibre mixed with acidified fishbones (Mix); middle row acidified fishbones (FB, left) and fresh fishbones (F); bottom row poultry manure (GO). Photo by Anne-Kristin Løes, October 14, 2020.

5 Conclusions and research needs

Our research has shown that acidified fishbone material from grinded and hydrolysed white fish species may contain significant amounts of nitrogen. For some time (weeks) after removal from the hydrolysis tank, the concentration may be close to the concentration in freshly grinded white fish backbones, where about 11% of the dry matter (DM) will be total N. After some months of storage, the total-N level seems to stabilise at about 4% of DM. By drying of fresh or acidified bone material from white fish species, it is possible to lose N. In most cases, however, drying will not reduce the total N concentration.

It should be further studied whether the initially high concentrations of tot-N found in relatively fresh acidified fish sediment are representative for this type of material when it is recently removed from hydrolysis tanks. Further, to maximise the utilisation of this valuable plant nutrient, we need to clarify which conditions may lead to losses of N during storage of fish material which shall be applied for fertilisation purpose.

Our research demonstrated that differences between fertiliser treatments may be clearly revealed in a pot experiment, but the yields obtained may not be very relevant for practical growing.

Application of high rates of fishbone material, and of algae fibre, may hamper the germination of seeds both from weeds and crop plants. This is likely due to high concentration of ammonium on the fishbone material, and a high pH and possibly high conductivity in the algae fibre. We did not assess conductivity of fertiliser materials in the studies presented here.

Fishbone material gave significantly better yields than mineral N fertiliser and poultry manure, even when the amount of N applied with fishbones was well below the amount applied with mineral N fertiliser and poultry manure. Acidified fish material has a remarkable effect on early plant growth.

To achieve a good effect on plant growth, it is more important to incorporate poultry manure to a significant soil depth, than it is for fish material.

Application of more than 300 kg total N per hectare does not significantly increase yield levels of ryegrass, and such high rates of fertiliser may cause tetany in ruminants if the plant material is applied as feed.

Application of algae fibre may increase the plant growth in the year of application for crops with a long period of nutrient uptake, such as leek. Algae fibre has a remarkable positive effect on subsequent crops, despite of a low content of phosphorus (P). This may be due to a high content of other minerals, such as potassium (K). Fishbones also increase the growth of subsequent crops, which is likely explained by the content of phosphorus and calcium (Ca), since the N is likely consumed in the first growing season.

Algae fibre increases soil pH and concentrations of AL-extractable K and magnesium (Mg), while acidified fish residues increase soil concentration of P-AL and Ca-AL. Residues of fresh fish do not affect soil P-AL in a short-time perspective (within one year).

A proposal for a new Norwegian regulation on organic fertilisers and soil amendments has proposed that the concentration of arsenic (As) should be < 5 mg kg^{-1} dry soil for Class 0; < 8 for Class I; < 16 for Class II and < 32 mg As kg^{-1} dry soil for Class III . If implemented, these levels will significantly hamper the use of brown seaweed material for fertilisation, especially because the regulation would not permit the “dilution” of materials exceeding 32 mg As kg^{-1} dry soil by other materials.

With the existing regulation, the concentration of cadmium (Cd) in seaweed is deciding the class of soil amendment for algae fiber. Five samples that were analysed all had 0.9-1.1 mg Cd kg^{-1} DM, which is above the limit for Class II, 0.8 mg Cd kg^{-1} DM. Hence, this material is Class II, whereas for other potentially toxic elements (PTEs) the material is Class 0 for Cr, Cu, Ni, Pb, and Zn. One sample had 0.8 mg of mercury (Hg) kg^{-1} DM, which is Class II, but on average the value was Class 0 also for Hg. Class II materials may be applied on agricultural soil with up to 20 tons of DM ha^{-1} over 10 years.

For fish residues rich in bone material, As, Hg and sink (Zn) should be considered if this material is applied as a soil amendment. The material may be Class I due to Hg, and hence and should not be applied with more than 40 tons of DM ha^{-1} over 10 years. However, to avoid excess application of N and P, the actual rates must be significantly lower and should never exceed 300 kg total N per hectare, and only on soils which will benefit from increased P-AL concentrations.

The rates of marine-derived material applied in the present study are realistic to assess effects on the concentrations of nutrients and PTEs in soil and plant material if we assume that the materials would be applied directly as soil amendments. Our research has shown that the fertilisation must be balanced to cover the crop nutrient demand, to avoid excess uptake of nutrients which may cause negative effects on animal health when the crop is applied for feed. Algae fiber should not be applied in rates higher than 10 tons of DM ha^{-1} to avoid tetany ratio levels which may induce tetany in ruminants in subsequent growing seasons; in the year of application, the plant material should not be applied as feed for ruminants. More research is required on different soil types and with different plant species to reveal which levels are beneficial and safe.

Application of algae fiber did increase soil concentrations of As and Cd, while no effects could be seen for Hg, possibly due to generally low concentrations of this element. No indications were found that application of fish material affected on soil PTE concentrations. In spite of the increased concentrations of As in soil no indications were found that application of algae fiber increased the concentration of As or Cd in aboveground plant material. We need more scientific studies under Norwegian conditions to study the fate of arsenic derived from marine materials in the plant-soil system.

A decomposition study revealed that organic materials buried into agricultural soil attract a lot of activity from soil-dwelling animals, and that the materials change their visual appearance and odor over time.

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Appendix 1 Plant composition: macro and micronutrients

Experiment 1, outdoor pot experiment with oats and leek 2019.

Concentrations of macronutrients and other elements. Each value represents the analysis of one bulked sample per treatment across replicates (n = 4). Analyses conducted by Actlabs, Canada. Values below the limit of quantification are shown in red and should be read as e.g., < 100.0 for Se.

Elements, leek	**Units**	**Control**	**Nmin_L**	**Nmin_H**	**Norg_L**	**Norg_H**	**Alg_L**	Alg_H	**Fish_L**	**Fish_H**	**Mix_L**	**Mix_H**
Total N	g / DW kg	18,4	17,9	18,2	18,7	15,0	19,8	17,4	8,4	10,5	11,1	8,9
P	g / DW kg	0,8	0,9	0,9	1,2	1,0	2,5	2,8	1,5	2,0	1,7	1,7
S	g / DW kg	2,0	2,1	2,0	1,8	1,4	2,7	2,4	0,8	0,9	1,3	1,1
K	g / DW kg	18,2	17,0	18,6	17,2	11,8	32,8	30,4	6,0	5,6	17,8	16,1
Mg	g / DW kg	1,4	1,4	1,4	1,5	1,2	2,2	2,3	1,0	1,2	1,2	1,1
Ca	g / DW kg	9,7	8,9	9,8	10,4	8,3	7,5	5,8	6,8	9,3	6,7	5,2
Na	g / DW kg	0,3	0,3	0,3	0,7	0,5	1,6	1,5	1,3	1,5	0,4	0,7
Fe	mg / DW kg	118,6	123,9	118,6	79,4	75,2	84,7	75,4	54,4	61,7	44,1	44,4
B	mg / DW kg	16,9	15,2	16,5	13,9	10,8	17,0	15,9	9,9	10,7	13,4	12,0
Mn	mg / DW kg	56,4	51,7	58,4	60,3	48,1	14,5	9,4	26,9	38,9	22,7	15,5
Mo	µg / DW kg	164,1	223,2	140,4	173,6	146,0	1018,1	1552,7	123,1	107,7	235,1	256,5
Se	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Al	mg / DW kg	89,9	90,1	91,9	55,9	62,0	51,9	47,0	37,6	47,0	31,1	31,3
Co	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0

Elements,oats	**Units**	**Control**	**Nmin_L**	**Nmin_H**	**Norg_L**	**Norg_H**	**Alg_L**	Alg_H	**Fish_L**	**Fish_H**	**Mix_L**	**Mix_H**
Total N	g / DW kg	21,4	22,5	22,0	19,9	22,1	14,2	15,6	17,0	18,3	12,1	15,6
P	g / DW kg	1,6	1,6	1,5	1,8	2,4	2,0	2,4	2,5	2,9	1,8	2,6
S	g / DW kg	2,0	2,2	2,0	1,5	2,0	1,4	1,5	1,4	1,5	1,1	1,4
K	g / DW kg	20,9	20,5	19,1	18,4	18,5	21,6	23,3	12,4	11,6	17,3	21,7
Mg	g / DW kg	1,7	1,6	1,5	1,4	1,6	1,6	1,5	1,9	1,9	1,2	1,4
Ca	g / DW kg	4,2	4,7	4,5	3,5	4,6	2,5	1,9	5,0	6,1	2,3	3,0
Na	g / DW kg	1,2	1,4	1,2	1,4	1,7	0,5	0,7	3,4	4,9	0,5	0,7
Fe	mg / DW kg	129,2	130,6	112,5	95,9	104,9	68,7	63,0	127,6	112,7	55,2	63,7
B	mg / DW kg	5,1	5,7	6,1	4,0	4,6	3,1	2,4	3,5	3,7	2,0	2,7
Mn	mg / DW kg	178,9	240,4	271,9	153,8	219,4	86,6	50,9	121,5	116,3	67,9	69,3
Mo	µg / DW kg	758,4	681,4	539,8	395,6	391,7	1334,4	1756,0	335,4	283,7	337,4	512,9
Se	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Al	mg / DW kg	73,9	66,6	59,0	46,2	55,0	35,5	26,4	75,7	54,5	24,3	30,4
Co	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0

Experiment 2, field experiment with oats in 2019 followed by 1st year ley in 2020 and 2dn year ley in 2022.

Concentrations of macronutrients and other elements **in oat plants which were harvested as green fodder in 2019.** Average values of four replicate samples per treatment. Analyses conducted by Actlabs, Canada. Values below the limit of quantification are shown in red and should be read as e.g., < 100.0 for Co.

Elements	Units	Control	Norg_H	Alg_H	Fish_H	Mix_H
Total N	g / DW kg	22,3	25,3	20,1	21,9	19,4
P	g / DW kg	2,4	3,1	2,8	3,7	3,7
S	g / DW kg	1,7	2,2	2,0	1,6	1,8
K	g / DW kg	18,0	20,9	26,8	14,0	27,8
Mg	g / DW kg	2,0	2,5	1,9	2,1	2,1
Ca	g / DW kg	3,0	4,3	2,2	4,5	3,6
Na	g / DW kg	3,0	3,7	1,8	4,4	2,1
Fe	mg / DW kg	76,1	85,1	80,5	79,1	94,2
B	mg / DW kg	4,7	6,8	4,8	5,3	7,0
Mn	mg / DW kg	90,8	112,0	89,4	79,9	86,8
Mo	µg / DW kg	1296,8	799,8	1370,1	799,0	953,2
Se	µg / DW kg	100,0	100,0	100,0	100,0	100,0
Co	µg / DW kg	100,0	100,0	100,0	100,0	100,0
Al	mg / DW kg	32,2	32,2	35,3	34,5	27,7

Experiment 2, continued

Concentration of macronutrients and other elements **in cut 1 and 2 of a 2^{nd} year ley in 2021,** amended with marine materials in 2019. Values for one bulked sample per treatment per cut across four replicate plots per treatment. Analyses conducted at Nemko Norlab.

Elements	Units	Control		Norg_H		Alg_H		Fish_H		Mix_H	
		Cut_1	Cut_2	Cut_1	Cut_2	Cut_1	Cut_2	Cut_1	Cut_2	Cut_1	Cut_2
Total N	g / DW kg	16,0	20,7	13,2	18,8	14,0	19,7	15,0	20,0	14,1	21,6
P	g / DW kg	1,5	1,6	1,9	2,2	1,5	1,8	2,6	2,7	2,2	2,5
S	g / DW kg	1,0	1,5	0,9	1,4	0,8	1,1	0,9	1,4	0,8	1,0
K	g / DW kg	12,0	10,0	9,9	9,2	22,0	27,0	9,1	9,5	20,0	18,0
Mg	g / DW kg	1,9	3,1	1,7	2,8	1,7	2,1	1,8	2,5	1,6	2,5
Ca	g / DW kg	7,9	13,0	7,2	9,8	4,9	7,8	7,8	8,2	5,6	8,8
Na	g / DW kg	0,4	0,7	0,2	0,4	0,0	0,1	0,5	0,4	0,1	0,2
Fe	mg / DW kg	38,0	52,0	38,0	51,0	33,0	45,0	40,0	61,0	35,0	45,0
B	mg / DW kg	140,0	110,0	140,0	95,0	240,0	140,0	190,0	85,0	180,0	110,0
Mn	mg / DW kg	52,0	78,0	52,0	72,0	20,0	28,0	52,0	66,0	31,0	41,0
Mo	µg / DW kg	750,0	1500,0	590,0	1600,0	800,0	1300,0	620,0	1300,0	580,0	1000,0
Se	µg / DW kg	64,0	41,0	25,0	20,0	61,0	21,0	65,0	43,0	62,0	25,0
Si	mg / DM kg	1800,0	2400,0	1600,0	2500,0	1400,0	2500,0	1700,0	2400,0	1300,0	2100,0
Ag	µg/ DM kg	85,0	85,0	85,0	85,0	85,0	85,0	85,0	85,0	85,0	85,0
Sn	µg/ DM kg	3800,0	3800,0	3800,0	3800,0	3800,0	3800,0	3800,0	3800,0	3800,0	3800,0
Co	µg/ DM kg	20,0	22,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0
Al	mg / DW kg	19,0	23,0	19,0	23,0	15,0	23,0	17,0	36,0	17,0	24,0

Experiment 3, field experiment with ryegrass in 2020 and residual crops in 2021.

Concentration of macronutrients and other elements **in ryegrass** fertilised with different mineral materials in a field experiment **in 2020**. Values for one bulked sample per treatment across replicate plots (n= 4) at each cut. Analyses conducted at Nemko Norlab.

Elements	Units	Control	Norg_L	Norg_H	Alg_L	Frish_L	Fish_L	Fish_H	Mix_L	Mix_H
Cut 1 - 30/06/2020 (n=1)										
Total N	g / DW kg	38	41	42	39	43	37	40	37	40
P	g / DW kg	2,7	3,1	3,6	3,2	3,4	4,4	5,1	4,1	4,8
S	g / DW kg	1,7	1,7	2,6	2,4	1,9	1,5	1,8	1,6	1,8
K	g / DW kg	40	42	41	35	38	33	32	39	36
Mg	g / DW kg	2,4	2,7	2,3	2,5	2,5	2,6	2,3	2,4	2,3
Ca	g / DW kg	4,1	3,7	4,2	4,5	4,7	5,4	5,1	4,5	4,2
Na	g / DW kg	1,1	1,9	1,6	2,7	1,9	4,8	5,2	4,2	5
Fe	mg / DW kg	71	120	99	99	92	78	87	80	78
B	mg / DW kg	300	360	270	300	330	300	300	320	300
Mn	mg / DW kg	68	86	81	76	71	69	66	67	67
Mo	µg / DW kg	2000	500	540	2300	290	1200	200	620	590
Se	µg / DW kg	25	25	25	25	25	25	25	25	55
Si	mg / DW kg	610	600	550	710	580	430	510	411	460
Ag	µg / DW kg	**140**	38	61	27	10	1000	25	12	12
Sn	µg / DW kg	38	15	15	15	50	870	15	15	1900
Co	µg/ DM kg	150,0	180,0	150,0	130,0	150,0	1100,0	170,0	120,0	94,0
Al	mg / DW kg	61,0	110,0	63,0	75,0	68,0	64,0	67,0	65,0	58,0
Cut 2 - 20/07/2020 (n=1)										
Total N	g / DW kg	33	40	41	43	38	31	43	39	39
P	g / DW kg	2,8	3,4	3,6	6	5,5	2,5	5,9	5,9	3,3
S	g / DW kg	1,6	3,1	3,3	1,6	1,8	1,1	1,6	2,1	1,7
K	g / DW kg	34	49	50	30	43	39	33	40	40
Mg	g / DW kg	1,6	1,9	1,6	2,2	2	2,4	2,6	2,1	2
Ca	g / DW kg	2,8	3,8	3,8	5,9	3,9	3,5	6,5	3,8	4,5
Na	g / DW kg	4,5	1,6	1,5	10	7,6	1,5	8,7	9,8	2,8
Fe	mg / DW kg	170	120	120	140	110	110	140	110	100
B	mg / DW kg	340	360	380	360	270	380	420	280	380
Mn	mg / DW kg	64	110	90	83	71	92	92	81	93
Mo	µg / DW kg	1300	280	180	180	780	970	300	840	260
Se	µg / DW kg	52	25	110	58	25	25	53	25	25
Si	mg / DW kg	410	400	400	410	430	500	420	390	510
Ag	µg / DW kg	17	15	16	15	20	19	18	20	39
Sn	µg / DW kg	15	15	15	15	15	15	15	15	15
Co	µg/ DM kg	130,0	150,0	120,0	190,0	140,0	150,0	180,0	120,0	180,0
Al	mg / DW kg	170,0	110,0	120,0	130,0	95,0	110,0	130,0	96,0	110,0
Cut 3 - 14/08/2020 (n=1)										
Total N	g / DW kg	34	23	37	33	29	26	26	32	31
P	g / DW kg	5,1	3,2	3,8	4,7	4,4	2,1	4,1	2,8	3,1
S	g / DW kg	1,3	1,6	2,1	1,5	1,1	0,84	1,1	1,1	2,4
K	g / DW kg	28	30	47	35	25	31	34	32	41
Mg	g / DW kg	2,1	1,5	1,5	1,7	1,9	1,5	1,6	1,6	1,5
Ca	g / DW kg	6,7	2,7	4,6	3,3	6	3,2	3,5	4,4	4,1
Na	g / DW kg	8,8	5,7	1,2	7,6	6,3	1,1	4,7	2,5	1,1
Fe	mg / DW kg	140	76	100	74	83	74	83	91	79
B	mg / DW kg	350	370	390	330	290	410	360	340	310
Mn	mg / DW kg	95	73	86	61	82	86	55	75	84
Mo	µg / DW kg	370	1300	2000	980	830	1000	900	400	470
Se	µg / DW kg	25	25	150	25	25	25	25	25	25
Si	mg / DW kg	530	470	490	340	430	450	310	420	380
Ag	µg / DW kg	33	24	180	17	82	14	28	15	37
Sn	µg / DW kg	42	42	160	15	64	15	15	15	52
Co	µg/ DM kg	270,0	150,0	170,0	100,0	160,0	120,0	97,0	110,0	110,0
Al	mg / DW kg	130,0	77,0	94,0	67,0	67,0	81,0	97,0	110,0	68,0
Cut 4 - 21/09/2020 (n=1)										
Total N	g / DW kg	23	29	21	21	29	34	28	26	33
P	g / DW kg	4,3	5,1	1,1	3,3	3,3	3,8	4,9	3,4	5,2
S	g / DW kg	1,1	1,4	0,25	0,87	1,1	2,3	1,3	1,9	1,5
K	g / DW kg	33	36	15	25	29	43	26	37	27
Mg	g / DW kg	1,5	1,7	0,66	1,5	1,6	1,5	1,5	1,4	1,9
Ca	g / DW kg	3,6	3,6	1,8	2,5	5,1	4,5	5,5	4,1	7,2
Na	g / DW kg	4,6	7,2	0,7	7,2	3,8	1,7	5,6	1,9	8,3
Fe	mg / DW kg	76	85	31	81	77	110	70	75	100
B	mg / DW kg	390	450	250	340	360	330	260	350	350
Mn	mg / DW kg	54	61	44	84	87	98	95	95	110
Mo	µg / DW kg	1100	990	480	1100	660	450	690	470	550
Se	µg / DW kg	75	100	25	25	45	25	25	25	25
Si	mg / DW kg	480	470	270	490	510	500	580	480	660
Ag	µg / DW kg	12	20	2,5	2,5	7,1	4,9	7,1	2,5	2,5
Co	µg/ DM kg	84,0	110,0	49,0	99,0	120,0	120,0	150,0	100,0	170,0
Sn	µg / DW kg	49	52	15	33	40	29	35	40	44
Al	mg / DW kg	76,0	82,0	27,0	91,0	69,0	110,0	56,0	70,0	96,0

Experiment 3, continued

Concentration of macronutrients and other elements in **oats harvested as green fodder in 2021**. The crop was grown in a field experiment to evaluate residual effects of marine materials applied for fertilisation of ryegrass in 2020. Values of one sample per treatment (one block only). Analyses conducted at Nemko Norlab.

Elements	Units	Control	Norg_L	Norg_H	Alg_L	FRish_L	Fish_L	Fish_H	Mix_L	Mix_H
Total N	g / DW kg	-	-	-	-	-	-	-	-	-
P	g / DW kg	2,1	2,5	2,5	2,5	2,6	3,3	3,7	3,0	3,7
S	g / DW kg	2,7	1,9	2,0	1,4	2,3	5,0	2,1	1,6	1,9
K	g / DW kg	20,6	18,2	18,6	18,9	18,7	17,7	15,1	19,9	21,9
Mg	g / DW kg	1,4	1,1	1,0	1,3	1,5	1,4	1,2	1,2	1,6
Ca	g / DW kg	3,0	2,7	2,6	1,8	3,6	3,9	3,5	2,8	2,6
Na	g / DW kg	0,6	0,6	0,7	2,6	1,6	2,3	1,9	2,2	2,7
Fe	mg / DW kg	49,1	43,7	38,2	40,9	49,9	45,7	44,7	42,9	48,9
B	mg / DW kg	74,2	102,0	84,0	125,1	92,7	74,8	59,9	116,0	73,6
Mn	mg / DW kg	108,5	112,8	108,7	36,9	111,8	79,2	131,3	38,7	42,2
Mo	µg / DW kg	646,2	660,6	652,9	1513,8	657,6	863,7	796,4	1063,0	1377,3
Se	µg / DW kg	80,5	2,5	9,9	67,8	30,7	33,6	2,5	98,1	59,8
Si	mg / DW kg	743,6	801,1	830,0	428,8	867,9	769,8	847,7	914,7	489,9
Ag	µg / DW kg	127,5	86,7	11,0	30,0	3,1	101,5	7,0	3,1	3,8
Sn	µg / DW kg	0,6	1,5	2,4	10,4	0,7	167,6	5,5	3,4	4,3
Co	µg/ DM kg	69,01	65,94	73,40	31,45	115,79	147,83	76,95	31,89	44,00
Al	µg/ DM kg	8,30	8,39	6,76	6,83	12,15	9,57	6,03	7,35	9,10

Experiment 3, continued

Concentrations of macronutrients and other elements in **potato tubers in 2021**. The potatoes were grown in a field experiment to evaluate residual effects of marine materials applied for fertilisation of ryegrass in 2020. Values are averages of 3 replicate samples (one per replicate block) per treatment. Analyses conducted at Nemko Norlab.

Elements	Units	Control	Norg_L	Norg_H	Alg_L	FRish_L	Fish_L	Fish_H	Mix_L	Mix_H
Total N	g / DW kg	-	-	-	-	-	-	-	-	-
P	g / DW kg	1,3	1,5	1,6	1,5	1,5	2,7	2,8	2,1	2,5
S	g / DW kg	0,7	0,5	0,6	0,5	0,5	0,5	0,8	0,7	0,4
K	g / DW kg	14,7	13,8	15,0	21,6	12,4	12,5	12,5	14,4	16,0
Mg	g / DW kg	0,8	0,8	0,9	1,2	0,8	0,7	0,6	0,9	0,9
Ca	g / DW kg	0,06	0,04	0,15	0,06	0,05	0,09	0,10	0,07	0,07
Na	g / DW kg	1,0	1,3	0,9	1,3	1,2	0,9	1,1	1,4	1,4
Fe	mg / DW kg	21,5	18,5	24,1	21,4	21,2	20,9	20,7	21,9	19,4
B	mg / DW kg	-	-	-	-	-	-	-	-	-
Mn	mg / DW kg	5,4	5,1	5,6	4,2	5,0	5,3	4,8	5,1	4,1
Mo	µg / DW kg	127,5	157,2	156,9	380,2	166,0	236,4	282,8	269,5	283,2
Se	µg / DW kg	-	-	-	-	-	-	-	-	-
Si	mg / DW kg	-	-	-	-	-	-	-	-	-
Ag	µg / DW kg	5,9	6,4	7,5	3,3	9,4	7,9	15,4	11,4	4,4
Sn	µg / DW kg	16,1	21,3	16,3	23,0	20,8	11,5	15,7	20,1	20,4
Co	µg/ DM kg	104,59	111,35	106,60	60,48	121,83	155,96	372,04	77,35	62,52
Al	µg/ DM kg	85,99	104,55	79,00	113,76	93,42	72,48	91,66	95,20	80,85

Appendix 2 Plant composition: potentially toxic elements

Experiment 1, outdoor pot experiment with oats and leek 2019.

Concentrations of potentially toxic elements in aboveground plant material of oats and leek, fertilised with marine materials in 2019. Bulked samples per treatment across replicates (n = 4). Analyses conducted by Actlabs, Canada. Values below the limit of quantification are shown in red and should be read as e.g., < 2.0 for Cr.

Elements, leek	**Units**	**Control**	**Nmin_L**	**Nmin_H**	**Norg_L**	**Norg_H**	**Alg_L**	**Alg_H**	**Fish_L**	**Fish_H**	**Mix_L**	**Mix_H**
Cr	mg / DW kg	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Pb	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Hg	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Ni	µg / DW kg	690,2	790,2	684,6	657,9	538,7	440,0	356,8	519,7	515,4	442,7	328,3
As	mg/ DW kg	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
Cd	µg / DW kg	176,1	140,8	194,2	121,1	65,8	53,3	40,5	64,5	71,2	60,7	49,2
Cu	mg / DW kg	3,1	3,6	3,2	3,6	3,0	3,5	3,5	2,2	2,6	2,4	2,2
Zn	mg / DW kg	27,2	25,6	28,0	19,6	14,9	19,3	17,8	10,2	9,7	10,2	9,6
Elements, oats	**Units**	**Control**	**Nmin_L**	**Nmin_H**	**Norg_L**	**Norg_H**	**Alg_L**	**Alg_H**	**Fish_L**	**Fish_H**	**Mix_L**	**Mix_H**
Cr	mg / DW kg	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Pb	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Hg	µg / DW kg	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Ni	µg / DW kg	1638,8	1457,9	1591,4	1146,0	1089,2	791,6	827,3	1132,9	1027,9	692,7	640,2
As	mg/ DW kg	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
Cd	µg / DW kg	44,7	55,5	71,2	31,4	32,5	17,6	16,2	30,7	33,2	13,9	13,9
Cu	mg / DW kg	6,5	6,8	9,1	5,4	6,0	4,0	3,8	4,0	4,1	3,2	3,2
Zn	mg / DW kg	43,8	49,7	52,6	37,0	50,5	24,5	22,3	39,4	37,0	27,2	25,7

Experiment 2, field experiment with oats in 2019 followed by 1st year ley in 2020 and 2dn year ley in 2022.

Concentration of potentially toxic elements in crops grown in a field experiment fertilised with marine materials in 2019. The oats crop in 2019 was harvested as green fodder; for 1st year ley in 2021 there were two cuts. Each value is an average of four replicate samples per treatment. Samples from 2019 analysed by Actlabs, Canada; samples from 2021 by Nemko Norlab. Values below the limit of quantification are shown in red and should be read as e.g., < 2.0 for Cr.

Elements	Units	Control		Norg_H		Alg_H		Fish_H		Mix_H	
						Oats - 2019					
Cr	mg / DW kg	2,0		2,0		2,0		2,0		2,0	
Pb	µg / DW kg	100,0		100,0		100,0		100,0		100,0	
Hg	µg / DW kg	100,0		100,0		100,0		100,0		100,0	
Ni	µg / DW kg	758,5		728,0		673,1		651,2		536,0	
As	mg/ DW kg	0,50		0,50		0,50		0,50		0,50	
Cd	µg / DW kg	73,1		94,5		78,5		62,7		92,9	
Cu	mg / DW kg	6,3		5,7		5,6		4,0		4,1	
Zn	mg / DW kg	57,1		68,5		49,3		47,0		52,1	
						2nd year ley - 2021					
		1st cut	**2nd cut**	**1st cut**	**2nd cut**	**1st cut**	**2nd cut**	**1st cut**	**2nd cut**	**1st cut**	**2nd cut**
Cr	mg / DM kg	0,27	0,44	0,37	0,71	0,42	0,29	0,42	0,89	0,29	0,40
Pb	µg/ DM kg	60	60	60	60	60	60	60	60	60	60
Hg	µg/ DM kg	700	700	700	700	700	700	700	700	700	700
Ni	µg/ DM kg	470	820	410	730	210	260	440	730	170	400
As	mg / DM kg	0,37	0,37	0,37	0,37	0,37	0,37	0,37	0,37	0,37	0,37
Cd	µg/ DM kg	28,0	21,0	25,0	12,0	5,0	8,6	15,0	10,0	5,6	12,0
Cu	mg / DW kg	4,3	8,9	2,7	6,7	1,9	5,8	2,3	5,1	1,4	5,4
Zn	mg / DW kg	32,0	41,0	32,0	35,0	19,0	25,0	32,0	29,0	22,0	28,0

Experiment 3, field experiment with ryegrass in 2020 and residual crops in 2021.

Concentration of potentially toxic elements **in ryegrass** fertilised with different mineral materials **in 2020**, over four cuts. Each value is an analysis of one bulked sample per treatment across replicate plots (n= 4) per cut. Analyses conducted at Nemko Norlab. Values below the limit of quantification are shown in red.

Elements	Units	Control	Norg_L	Norg_H	Alg_L	Frish_L	Fish_L	Fish_H	Mix_L	Mix_H
Cut 1 - 30/06/2020 (n=1)										
Cr	mg / DM kg	0,31	0,51	0,21	0,60	0,26	1,20	0,34	0,35	0,29
Pb	µg/ DM kg	150,0	170,0	130,0	120,0	110,0	1000,0	82,0	69,0	59,0
Hg	µg/ DM kg	200,0	200,0	200,0	200,0	200,0	200,0	100,0	100,0	350,0
Ni	µg/ DM kg	590,0	780,0	630,0	620,0	780,0	1700,0	680,0	460,0	340,0
As	mg / DM kg	0,46	0,20	0,22	0,22	0,07	1,10	0,15	0,11	0,16
Cd	µg/ DM kg	55,0	170,0	150,0	57,0	120,0	190,0	120,0	82,0	100,0
Cu	mg / DW kg	8,8	9,3	10,0	9,4	10,0	9,4	9,0	7,7	7,1
Zn	mg / DW kg	42,0	54,0	50,0	37,0	50,0	42,0	42,0	36,0	39,0
Cut 2 - 20/07/2020 (n=1)										
Cr	mg / DM kg	0,92	0,52	0,58	0,89	0,47	0,49	0,74	0,54	0,38
Pb	µg/ DM kg	130,0	130,0	150,0	110,0	82,0	140,0	110,0	90,0	110,0
Hg	µg/ DM kg	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0
Ni	µg/ DM kg	450,0	670,0	720,0	890,0	400,0	610,0	850,0	360,0	620,0
As	mg / DM kg	0,15	0,10	0,10	0,11	0,17	0,11	0,10	0,17	0,13
Cd	µg/ DM kg	35,0	130,0	67,0	50,0	75,0	86,0	70,0	74,0	130,0
Cu	mg / DW kg	6,6	8,9	9,2	9,9	7,4	7,7	9,1	7,8	8,9
Zn	mg / DW kg	24,0	40,0	34,0	32,0	29,0	40,0	34,0	31,0	38,0
Cut 3 - 14/08/2020 (n=1)										
Cr	mg / DM kg	0,75	0,40	0,56	0,46	0,39	0,36	0,43	0,50	0,39
Pb	µg/ DM kg	150,0	95,0	210,0	85,0	120,0	120,0	100,0	130,0	120,0
Hg	µg/ DM kg	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0
Ni	µg/ DM kg	1000,0	260,0	710,0	230,0	550,0	480,0	290,0	560,0	570,0
As	mg / DM kg	0,12	0,17	0,51	0,17	0,19	0,09	0,13	0,09	0,11
Cd	µg/ DM kg	54,0	20,0	34,0	60,0	50,0	55,0	36,0	30,0	26,0
Cu	mg / DW kg	8,4	5,3	7,4	4,7	5,7	5,8	4,1	6,2	7,0
Zn	mg / DW kg	32,0	23,0	33,0	23,0	25,0	27,0	19,0	23,0	28,0
Cut 4 - 21/09/2020 (n=1)										
Cr	mg / DM kg	0,37	0,56	0,05	0,59	0,40	0,47	0,41	0,35	0,51
Pb	µg/ DM kg	90,0	78,0	53,0	72,0	110,0	120,0	76,0	96,0	98,0
Hg	µg/ DM kg	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0
Ni	µg/ DM kg	310,0	310,0	160,0	320,0	550,0	540,0	550,0	460,0	650,0
As	mg / DM kg	0,08	0,10	0,01	0,06	0,06	0,04	0,04	0,01	0,01
Cd	µg/ DM kg	25,0	25,0	9,3	13,0	21,0	24,0	19,0	18,0	28,0
Cu	mg / DW kg	3,9	4,7	2,2	3,8	6,6	6,0	5,5	5,9	7,6
Zn	mg / DW kg	24,0	24,0	11,0	20,0	27,0	32,0	25,0	24,0	30,0

Experiment 3, continued

Concentration of potentially toxic elements **in oats and potatoes (tubers) in 2021.** Crops were grown in a field experiment to evaluate residual effects of marine materials applied for fertilisation of ryegrass in 2020. Oats were harvested as green fodder; values of one sample per treatment. Values for potato are averages of 3 replicate samples per treatment. Analyses conducted at Nemko Norlab. Values below the limit of quantification are shown in red.

Elements	Units	Control	Norg_L	Norg_H	Alg_L	FRish_L	Fish_L	Fish_H	Mix_L	Mix_H
Oats - 2021										
Cr	mg / DM kg	0,39	0,45	0,13	0,29	0,32	0,90	0,13	0,31	0,29
Pb	µg/ DM kg	43,3	54,7	25,7	41,9	18,3	105,3	15,4	6,7	12,1
Hg	µg/ DM kg	53,7	82,3	2,1	45,3	8,9	128,0	3,2	6,6	6,0
Ni	µg/ DM kg	576,1	641,5	466,4	326,5	518,0	619,9	619,3	358,6	299,9
As	mg / DM kg	0,003	0,007	0,024	0,050	0,010	0,098	0,021	0,044	0,043
Cd	µg/ DM kg	49,4	46,7	50,8	17,7	75,5	52,6	40,2	30,9	55,2
Cu	mg/ DM kg	7,7	5,4	4,1	4,2	5,6	3,9	3,8	3,4	3,2
Zn	mg/ DM kg	43,4	35,0	33,5	28,0	48,4	33,7	31,5	25,3	30,4
Potato - 2021										
Cr	mg / DM kg	0,03	0,04	0,07	0,08	0,05	0,04	0,07	0,08	0,04
Pb	µg/ DM kg	42,1	61,4	69,1	74,2	94,1	40,8	73,9	62,9	56,3
Hg	µg/ DM kg	19,8	21,1	16,7	22,5	20,0	15,7	17,6	17,3	16,4
Ni	µg/ DM kg	239,3	200,0	275,5	55,1	277,3	303,9	259,7	140,2	77,5
As	mg / DM kg	0,013	0,015	0,017	0,013	0,013	0,015	0,021	0,020	0,015
Cd	µg/ DM kg	44,2	42,0	43,3	36,7	49,6	58,8	50,9	53,3	48,2
Cu	mg/ DM kg	4,9	4,0	4,0	3,9	4,1	3,9	3,9	2,9	1,9
Zn	mg/ DM kg	13,9	11,9	11,3	12,5	12,2	12,0	10,5	10,0	8,7

Appendix 3 Potentially toxic elements in soil

Experiment 1, outdoor pot experiment with oats and leek 2019.

Soil concentrations of potentially toxic elements in two batches of sieved soil applied in the pots experiment (Initial soil), and and after harvest in July 2019 for oats and August 2019 for leek where each value represents one compiled sample per treatment across replicate pots. Analyses conducted by Eurofins. Values below the limit of quantification are shown in red and should be read as e.g., < 2.0 for As.

Elements	Units	Initial soil	Control	Nmin_L	Nmin_H	Norg_L	Norg_H	Alg_L	Alg_H	Fish_L	Fish_H	Mix_L	Mix_H
						Leek							
Cr	mg/kg DM	22,0	16,0	18,0	16,0	16,0	17,0	16,0	16,0	15,0	14,0	16,0	18,0
Ni	mg/kg DM	10,0	9,0	10,0	8,0	8,0	9,0	9,0	9,0	8,0	8,0	8,0	8,0
Cu	mg/kg DM	7,0	7,0	9,0	6,0	6,0	8,0	5,0	6,0	5,0	5,0	5,0	5,0
Zn	mg/kg DM	31,0	30,0	37,0	24,0	23,0	25,0	24,0	24,0	22,0	22,0	22,0	23,0
As	mg/kg DM	-	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Cd	mg/kg DM	0,20	0,10	0,20	0,10	0,10	0,20	0,20	0,20	0,10	0,10	0,10	0,20
Hg	mg/kg DM	0,02	0,02	0,03	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Pb	mg/kg DM	3,0	5,0	9,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
						Oats							
Cr	mg/kg DM	15,0	14,0	13,0	13,0	12,0	14,0	14,0	15,0	13,0	14,0	14,0	15,0
Ni	mg/kg DM	6,0	8,0	7,0	7,0	6,0	7,0	8,0	8,0	7,0	8,0	8,0	8,0
Cu	mg/kg DM	4,0	6,0	6,0	5,0	5,0	6,0	5,0	6,0	5,0	6,0	5,0	6,0
Zn	mg/kg DM	23,0	21,0	19,0	19,0	18,0	19,0	19,0	21,0	19,0	20,0	20,0	21,0
As	mg/kg DM	-	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Cd	mg/kg DM	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20
Hg	mg/kg DM	0,01	0,03	0,02	0,02	0,02	0,02	0,02	0,02	0,01	0,02	0,02	0,02
Pb	mg/kg DM	3,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0

Experiment 2, field experiment with oats in 2019 followed by 1st year ley in 2020.

Soil concentrations of potentially toxic elements before application of fertilisers, and after harvest of two crops (oats in 2019, ley in 2020). Each value is an average of one representative sample of topsoil (0-20 cm) per plot (n=4). Analyses conducted by Eurofins for samples from Spring 2019 and by Nemko Norlab for Autumn 2020.

Elements	Units	Control	Norg_H	Alg_H	Fish_H	Mix_H
			Spring 2019			
As-AL	mg/kg DM	-	-	-	-	-
Cr	mg/kg DM	12,25	9,50	12,50	11,50	11,25
Ni	mg/kg DM	4,75	4,25	5,00	5,25	4,75
Cu	mg/kg DM	3,75	5,00	3,75	5,25	4,25
Zn	mg/kg DM	28,25	31,25	34,50	35,50	31,25
As	mg/kg DM	< 2,0	< 2,0	< 2,0	< 2,0	< 2,0
Cd	mg/kg DM	0,20	0,18	0,18	0,18	0,20
Hg	mg/kg DM	0,04	0,04	0,04	0,04	0,04
Pb	mg/kg DM	4,25	4,50	4,75	5,00	4,50
			Autumn 2020			
As-AL	mg/kg DM	0,07	0,08	0,09	0,07	0,07
Cr	mg/kg DM	8,30	8,88	8,18	7,18	7,90
Ni	mg/kg DM	4,55	5,05	4,70	4,08	4,53
Cu	mg/kg DM	3,88	4,80	5,85	5,98	4,83
Zn	mg/kg DM	27,50	33,50	31,50	33,25	29,00
As	mg/kg DM	0,65	0,60	0,81	0,55	0,66
Cd	mg/kg DM	0,06	0,05	0,07	0,05	0,06
Hg	mg/kg DM	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70
Pb	mg/kg DM	5,08	5,13	4,90	5,78	5,35

Experiment 3, field experiment with ryegrass in 2020.

Soil concentrations of potentially toxic elements before application of fertilisers in May 2020, and after harvest of ryegrass (four cuts) in October 2020. Each value is an average of one representative sample of topsoil (0-20 cm) per plot (n= 4). Analyses conducted by Nemko Norlab.

Elements	Units	Control	Norg_L	Norg_H	Alg_L	FRish_L	Fish_L	Fish_H	Mix_L	Mix_H
					Spring					
As-AL	mg/kg DM	0,08	0,09	0,09	0,09	0,08	0,08	0,09	0,08	0,08
Cr	mg/kg DM	16,75	16,75	16,50	18,25	16,50	17,50	17,50	17,25	15,75
Ni	mg/kg DM	9,93	9,88	10,23	10,68	10,15	10,48	10,30	10,10	8,98
Cu	mg/kg DM	8,20	8,03	9,20	7,78	9,30	8,90	8,85	9,40	6,65
Zn	mg/kg DM	42,00	44,25	43,75	43,25	42,75	38,75	41,50	51,00	45,00
As	mg/kg DM	0,85	0,87	0,83	0,85	0,81	0,85	0,87	0,83	0,82
Cd	mg/kg DM	0,06	0,06	0,06	0,06	0,07	0,06	0,06	0,07	0,07
Hg	mg/kg DM	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70
Pb	mg/kg DM	7,85	8,18	8,05	6,65	7,63	6,30	6,93	6,55	5,65
					Autumn					
As-AL	mg/kg DM	0,06	0,06	0,07	0,12	0,07	0,06	0,07	0,08	0,07
Cr	mg/kg DM	13,75	12,50	12,65	14,75	11,90	11,45	13,80	12,50	11,63
Ni	mg/kg DM	8,20	8,75	7,83	9,35	7,58	7,18	8,38	7,45	6,95
Cu	mg/kg DM	7,25	22,33	7,40	7,38	7,10	6,15	7,48	6,60	5,55
Zn	mg/kg DM	44,00	30,00	30,75	33,75	27,00	24,25	30,75	26,75	29,00
As	mg/kg DM	0,67	0,56	0,55	1,28	0,52	0,51	0,61	0,65	0,76
Cd	mg/kg DM	0,05	0,04	0,04	0,07	0,04	0,04	0,04	0,05	0,05
Hg	mg/kg DM	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70	< 0,70
Pb	mg/kg DM	6,83	6,55	6,03	6,00	6,25	5,28	5,70	4,88	4,58

Appendix 4 Soil chemical characteristics

Experiment 1, outdoor pot experiment with oats and leek 2019 (continues on next page).

Soil concentrations of potentially toxic elements in two batches of sieved soil applied in the pots experiment (Initial soil), and and after harvest in July 2019 for oats and August 2019 for leek where each value represents one compiled sample per treatment across replicate pots. Analyses conducted by Eurofins. Values below the limit of quantification are shown in red and should be read as e.g., < 2.0 for As.

Row Labels	**pH**		**P-AL**		**Mg-AL**		**K-AL**		**Ca-AL**		**K(HNO_3)**		**Olsen-P**	
							Oats							
Initial soil	**5,7**	-	**20**	-	**39**	-	**43**	-	**640**	-	**1100**	-	-	-
Control	6,1	abc	27,0	b	120,8	ab	38,8	de	2462,5	a	1037,5	cd	12,5	B
Nmin_L	5,8	bc	18,0	b	31,3	b	34,3	e	647,5	a	915,0	d	12,5	B
Nmin_H	5,8	bc	18,0	b	26,8	b	32,8	e	635,0	a	955,0	cd	12,5	B
Norg_L	6,0	bc	24,0	b	35,0	b	35,3	e	652,5	a	925,0	d	12,5	B
Norg_H	5,6	c	27,8	b	30,8	b	36,8	e	617,5	a	897,5	d	12,5	B
Alg_L	6,4	ab	20,5	b	95,3	ab	202,5	b	757,5	a	1225,0	b	12,5	b
Alg_H	6,8	a	23,0	b	167,5	a	370,0	a	927,5	a	1450,0	a	12,5	b
Fish_L	5,9	bc	58,3	a	33,8	b	32,5	e	700,0	a	915,0	d	19,0	a
Fish_H	5,9	bc	74,5	a	31,0	b	35,3	e	717,5	a	932,5	cd	29,8	b
Mix_L	6,0	bc	29,8	b	53,5	b	64,3	d	690,0	a	1015,0	cd	12,5	b
Mix_H	6,2	abc	77,8	a	70,3	ab	98,5	c	830,0	a	1075,0	c	29,5	a

Row Labels	**pH**		**P-AL**		**Mg-AL**		**K-AL**		**Ca-AL**		**$K(HNO_3)$**		**Olsen-P**	
							Leek							
Initial soil	**5,5**	**-**	**24**	**-**	**51**	**-**	**49**	**-**	**750**	**-**	**1200**	**-**	**-**	
Control	5,5	de	25,5	e	35,5	de	47,8	cde	615,0	e	922,5	c	12,5	d
Nmin_L	5,5	de	25,5	e	29,0	e	44,8	cde	625,0	e	917,5	c	12,5	d
Nmin_H	5,4	de	25,8	e	27,0	e	43,3	de	630,0	e	947,5	c	12,5	d
Norg_L	5,4	de	45,8	de	33,3	e	47,8	cde	642,5	e	890,0	c	19,0	cd
Norg_H	5,3	e	72,8	cde	32,3	e	55,0	cde	662,5	de	937,5	c	29,3	cd
Alg_L	6,3	b	42,5	de	140,0	b	232,5	b	910,0	bc	1225,0	b	17,1	cd
Alg_H	6,9	a	37,5	de	237,5	a	380,0	a	1100,0	a	1425,0	a	17,5	cd
Fish_L	5,5	de	119,8	bc	32,3	e	35,8	e	780,0	cd	947,5	c	64,5	b
Fish_H	5,7	cd	200,0	a	49,5	cde	65,8	cde	927,5	b	980,0	c	99,8	a
Mix_L	6,0	bc	89,5	bcd	80,8	cd	105,0	cd	892,5	bc	940,0	c	47,0	bc
Mix_H	6,1	bc	142,5	b	81,3	c	110,5	c	965,0	b	935,0	c	74,5	ab

Experiment 2, field experiment with oats in 2019 followed by 1st year ley in 2020.

Values	pH		P-AL		Mg-AL		K-AL		Ca-AL		(KHNO3)	
Spring 2019												
Control	5,73	a	23,0	a	45,0	a	39,5	b	855,0	a	625,0	a
Norg_H	5,73	a	23,8	a	41,0	a	41,3	b	785,0	a	612,5	a
Alg_H	5,78	a	22,8	a	50,0	a	112,3	a	795,0	a	657,5	a
Fish_H	5,78	a	32,8	a	45,0	a	38,8	b	897,5	a	612,5	a
Mix_H	5,73	a	27,5	a	45,0	a	34,3	b	877,5	a	577,5	a
Autumnn 2020												
Control	5,6	b	38,5	c	42,3	b	31,5	b	415,0	a	-	-
Norg_H	5,6	b	47,8	bc	48,0	b	37,5	b	427,5	a	-	-
Alg_H	6,0	a	36,5	c	80,3	a	135,0	a	480,0	a	-	-
Fish_H	5,6	ab	80,3	a	43,5	b	30,3	b	470,0	a	-	-
Mix_H	5,7	ab	57,8	b	54,5	b	40,8	b	447,5	a	-	-

Autumn 2020

Elements	Units	Control	Norg_H	Alg_H	Fish_H	Mix_H
B	mg/kg DM	0,25	0,25	0,25	0,25	0,25
Al	g/kg DM	7,53	7,75	7,50	6,93	7,43
Si	mg/kg DM	31,00	34,50	29,50	30,00	33,75
Mn	mg/kg DM	108,75	118,75	104,50	112,25	116,50
Fe	g/kg DM	5,88	6,13	5,75	5,28	6,03
Se	µg/kg DM	20,25	19,75	18,50	18,50	20,75
Mo	mg/kg DM	0,39	0,40	0,39	0,36	0,37
Ag	mg/kg DM	0,09	0,09	0,09	0,09	0,09
S	g/kg DM	1,20	1,20	1,20	1,20	1,20
Sn	mg/kg DM	3,80	3,80	3,80	3,80	3,80
Co	mg/kg DM	2,23	2,38	2,25	2,05	2,23

Experiment 3, field experiment with ryegrass in 2020 (continues on next page).

	pH		P-AL		Mg-AL		K-AL		Ca-AL	
			mg/kg dry soil							
Spring										
Control	5,5		37,5		55,3		145,0		400,0	
Norg_L	5,5		38,5		58,0		146,8		425,0	
Norg_H	5,4		42,0		59,5		140,0		435,0	
Alg_L	5,5		39,8		58,5		130,0		447,5	
FRish_L	5,4		39,0		55,8		152,5		430,0	
Fish_L	5,4		39,8		59,3		137,5		450,0	
Fish_H	5,5		43,3		60,0		162,5		440,0	
Mix_L	5,5		42,8		52,3		146,3		387,5	
Mix_H	5,4		41,3		54,0		145,0		442,5	
Autumn										
Control	5,5	d	26,3	d	37,8	d	80,3	b	265,0	d
Norg_L	5,5	d	32,5	d	28,3	d	76,8	b	230,0	d
Norg_H	5,3	d	36,8	cd	30,0	d	89,8	b	245,0	d
Alg_L	7,2	a	22,5	d	175,0	a	260,0	a	537,5	a
FRish_L	5,4	d	30,3	d	32,3	d	58,5	b	252,5	d
Fish_L	5,5	d	77,8	b	31,0	d	56,0	b	315,0	cd
Fish_H	5,6	d	118,0	a	27,8	cd	53,3	b	367,5	bc
Mix_L	6,1	c	56,3	bcd	50,8	c	76,0	b	360,0	bc
Mix_H	6,5	b	74,0	bc	74,3	b	104,8	b	440,0	b

Elements	Units	Control	Norg_L	Norg_H	Alg_L	FRish_L	Fish_L	Fish_H	Mix_L	Mix_H
Spring										
B	mg/kg DM	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25
Al	g/kg DM	12,00	11,75	12,25	11,75	11,25	8,75	11,75	12,00	11,25
Si	mg/kg DM	42,00	44,25	45,25	45,50	45,00	37,50	41,25	41,75	41,50
Mn	mg/kg DM	192,50	187,50	192,50	195,00	190,00	200,00	192,50	187,50	175,00
Fe	g/kg DM	14,75	14,00	14,48	15,00	13,65	14,25	15,00	14,23	12,85
Se	µg/kg DM	28,25	27,25	29,00	25,50	27,75	27,50	26,75	31,25	29,75
Mo	mg/kg DM	0,38	0,38	0,38	0,38	0,43	0,38	0,49	0,41	0,40
Ag	mg/kg DM	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
S	g/kg DM	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00
Sn	mg/kg DM	3,80	3,80	3,80	3,80	3,80	3,80	3,80	3,80	3,80
Co	mg/kg DM	4,50	4,43	4,63	4,78	4,58	4,75	4,75	4,53	4,00
Autumn										
B	mg/kg DM	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25
Al	g/kg DM	9,88	10,05	10,35	10,03	9,48	10,15	10,78	9,98	9,68
Si	mg/kg DM	69,08	60,55	59,04	66,56	61,16	51,91	59,97	60,84	57,47
Mn	mg/kg DM	167,50	143,75	145,75	172,50	138,00	136,75	155,00	143,25	129,75
Fe	g/kg DM	9,05	8,23	8,20	9,65	7,70	7,53	8,80	7,65	7,48
Se	µg/kg DM	24,75	22,25	25,00	23,25	22,75	19,25	22,75	26,00	25,00
Mo	mg/kg DM	0,32	0,27	0,27	0,36	0,29	0,23	0,28	0,29	0,32
Ag	mg/kg DM	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
S	g/kg DM	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00
Sn	mg/kg DM	3,80	3,80	3,80	3,80	3,80	3,80	3,80	3,80	3,80
Co	mg/kg DM	3,78	3,43	3,53	4,10	3,40	3,25	3,80	3,23	3,03

Norsk senter for økologisk landbruk, NORSØK er ei privat, sjølvstendig stifting.
Stiftinga er eit nasjonalt senter for tverrfagleg forsking og kunnskapsformidling for å utvikle økologisk landbruk. NORSØK skal bidra med kunnskap for eit meir berekraftig landbruk og samfunn. Fagområda er økologisk landbruk og matproduksjon, miljø og fornybar energi.

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