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Carbon footprint and energy use of recycled fertilizers in arable farming

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Highlights

- No statistically significant differences in yields between the fertilizers.
- Lower energy use and emissions with recycled than mineral fertilizers.
- Notable differences in emissions and energy use between recycled fertilizers.
- Effect of data sources and allocation methods were considerable.

Abstract

The globally growing demand to produce more food with fewer inputs, less energy, and lower greenhouse gas (GHG) emissions challenges current agricultural practices. Recycled fertilizers made of various side streams and types of biomass have been developed mainly to improve nutrient recycling in food systems. However, the knowledge of the impacts of different recycled fertilizers on GHG emissions and energy use is lacking. There is also a need for developing environmental assessment methods for quantifying the impacts of recycling processes, particularly in terms of choosing reasonable methods for co-product allocation.

The aims of this study were to address the above mentioned research gaps by i) assessing energy use and GHG emissions of various recycled fertilizers, ii) comparing the recycled fertilizers with mineral fertilizers, and iii) comparing the impacts of using different co-product allocation methods for the recycled fertilizers. Attributional Life Cycle Assessment (LCA) was used for estimating energy use and GHG emissions of recycled fertilizers, including ammonium sulfate, biogas digestate, and meat and bone meal, using kg of nitrogen in the fertilizers as a functional unit. In addition, the energy use and GHG emissions of oat production when using the recycled and mineral fertilizers were quantified. The data were obtained from field experiments, LCA databases, published literature, and fertilizer companies.

The life-cycle energy consumption and GHG emissions of recycled fertilizers were found to be lower than that of mineral fertilizer, but also differences between recycled fertilizer products were notable. The biggest differences between fertilizers occurred in manufacturing and transportation.

However, this conclusion is highly sensitive to several decisions, such as data sources and LCA methods used. Handling the raw materials of recycled fertilizers as by-products instead of residues adds burdens from primary production to fertilizers. Also handling the materials as waste increases the impacts due to burdens from the recycling process. Since the raw materials of fertilizers have only little economic value, applying economic allocation results to significantly lower impacts than mass allocation.

Consequential LCA studies would be needed to improve the understanding of the wider impacts of recycled fertilizers, e.g. considering the benefits of avoided waste management processes.

Keywords

Life cycle assessment; meat and bone meal; ammonium sulfate; biogas digestate; nutrient recycling; allocation

Abbreviations

AS = ammonium sulfate; BD = biogas digestate; CFF = circular footprint formula; EA = economic allocation; GHG = greenhouse gas; LCA = life cycle assessment; MBM = meat and bone meal; N = nitrogen; T = transportation; Z = no fertilization

1. Introduction

The impacts of mineral fertilizers on the carbon footprint of agricultural products is significant – the production and use of inorganic fertilizers in agriculture account on average for 14% of the total carbon footprints of diets consumed in the European Union (Sandström et al., 2018). In addition, the flows of nitrogen (N) and phosphorus have already crossed the planetary boundaries that determine the safe operating space for humanity (Rockström et al., 2009; Steffen et al., 2015). Therefore, the agricultural industry should aim to produce food with reduced nutrient losses, greenhouse gas (GHG) emissions, and consumption of energy and raw materials.

Utilization of side streams from industry to fertilizer usage is an option for reducing the use of mineral fertilizers. Most considerable alternatives are biomass sources generated in great amounts and with a high nutrient content (Marttinen et al., 2018). Nevertheless, many biomass sources are not suitable for direct application on fields and require pre-processing, which increases energy consumption and causes GHG emissions. The nutrient concentration of recycled fertilizers can be considerably lower than in mineral fertilizers, and therefore, the amount of fertilizer applied per unit area needs to be multiplied, resulting in higher environmental impacts from transport, storage, and application of the fertilizers. Correspondingly, a lower application rate of the fertilizers may result in lower grain yields and thus inefficient land use. Enhancing nutrient recycling can reduce the environmental impact of agriculture and save non-renewable resources and energy in fertilizer production (Marttinen et al., 2018). However, the life cycle based environmental impacts of recycled fertilizers needs to be quantified in order to understand the total environmental impacts.

The estimation of environmental impacts of recycled product face methodological challenges, especially in terms of allocating the impact of the whole system between all products of the system. Life cycle assessment (LCA), that is commonly used for analyzing environmental impacts of products and services, provides several allocation methods that can be applied for material recycling (European Commission, 2018; ISO 14040:2006). Those allocation options include the following: i) raw materials of recycled fertilizers can be regarded as residues with no economic value and are handled in LCA with no burden from the system generating them, ii) the materials can be handled as co-products and the impacts are allocated to these products based on economic value or physical attributes, iii) the materials can be handled as waste and impacts from the end-of-life/recycling process are allocated between the system producing the waste and system using the material (European Commission, 2018; ISO 14040:2006).

The second approach is often adapted if the materials leave the system and are used in other systems. However, manure is usually considered as waste without allocation of any burden from the livestock production to it, even though manure could be handled as a co-product when it is used to replace fertilizers (Leip et al., 2019; Little et al., 2017). Since, according to the ISO standard, allocation should be based on a physical relationship before economic allocation, it is discussed whether, for example, manure should be handled as a co-product even when it has no economic value (Leip et al., 2019). These methodological allocation choices affect the results of LCA studies. For example, whether the allocation of meat and bone meal (MBM) is based on mass, energy content, or market value, the allocation factor can vary between 1 and 21% (Esteves et al., 2017).

The fertilizer effect of recycled fertilizer products and general environmental benefits have been studied previously but a closer comparison of environmental impacts of different recycled fertilizer product types has not been done (Brockmann et al., 2018; Chen et al., 2011; Jeng et al., 2004; Jeng et al., 2007; Möller & Müller, 2012; Mondini et al., 2008; Nogalska et al., 2014; Razon, 2012). The assessment methods used also differ between studies, making comparison of results from different studies difficult (Brockmann et al., 2018; Rivera et al., 2017). In this study, the energy consumption and GHG emissions of mineral fertilizers and the recycled fertilizers, ammonium sulfate (AS), biogas digestate (BD), and MBM, are examined. The aims of this study are to assess energy use and GHG emissions of recycled fertilizers, compare the different recycled fertilizer and mineral fertilizers, and test and compare different allocation methods for the recycled fertilizers.

2. Materials and methods

2.1 Overview of the methods

LCA (ISO 14040:2006) was used to estimate the life-cycle energy consumption, and GHG emissions of oat (*Avena sativa*) production when using the recycled fertilizers AS, MBM, and BD. As a comparison, also mineral fertilizers with two different application rates and no fertilization were included. The GHG emissions were converted to CO_2 equivalents (CO_2-eq) according to the 100-year global warming potential coefficients used in the fifth Intergovernmental Panel on Climate Change (IPCC) assessment report and the impact assessment of energy use was conducted using Cumulative Energy Demand method (IPCC, 2014).

2.2 Studied fertilizers

2.2.1 Ammonium sulfate

AS can be produced from a variety of raw materials such as side streams of the nickel industry, BD, and livestock manure, but in this study it is assumed to originate from nylon production. The AS generated in the process can be further processed into crystal form when storing and transporting becomes more efficient. AS crystals can be dissolved in water and applied to a field by a sprayer (Soilfood, 2018).

2.2.2 Meat and bone meal

The MBM used in fertilizers is made from animal by-products such as carcasses collected from farms or rejected material from slaughterhouses (Lehtinen, 2018). In processing the material, the raw material is crushed, heated, sterilized, and dried. Finally, the grease and solid matter are separated by compression. The protein meal is cooled, comminuted, and delivered to the fertilizer factory and the fat is further processed to biodiesel (Lehtinen, 2018). The components of the fertilizer, meat and bone meal, oat hulls, vinasse and granulated poultry manure, are mixed and pelleted, after which they are suitable to be used in the same way as mineral fertilizers.

2.2.3 Biogas digestate

For biogas production, several agricultural side streams such as manure and plant waste, as well as municipal wastes such as biowaste and wastewater, are suitable raw materials (Möller & Müller, 2012). In the process, organic materials are decomposed by microbes under oxygen-free conditions. The digestion residue contains the same nutrients as the feedstock, but the composition changes in the digestion process, leading to potential benefits concerning, for example, N availability (Möller & Müller, 2012). The BD is suitable to be used as a fertilizer directly from a biogas plant and does not need to be processed further.

2.3 Functional unit, system boundaries and allocations

A ton (1000 kg) of oats, field hectare, and a kilogram of N in fertilizers were used as the functional units of the study to consider the possible effects of differences in yields, field operations, and application rates.

For the functional units a ton of oats and field hectare, the baseline system boundary included the manufacturing of fertilizer for AS, MBM and MF, fertilizer application for AS and BD and for all fertilizers transportation, sowing, harvesting, direct soil emissions, and indirect soil emissions

(Figure 1). For the functional unit of N kg in fertilizers, only manufacturing, transportation, fertilizer application, and soil emissions were included.

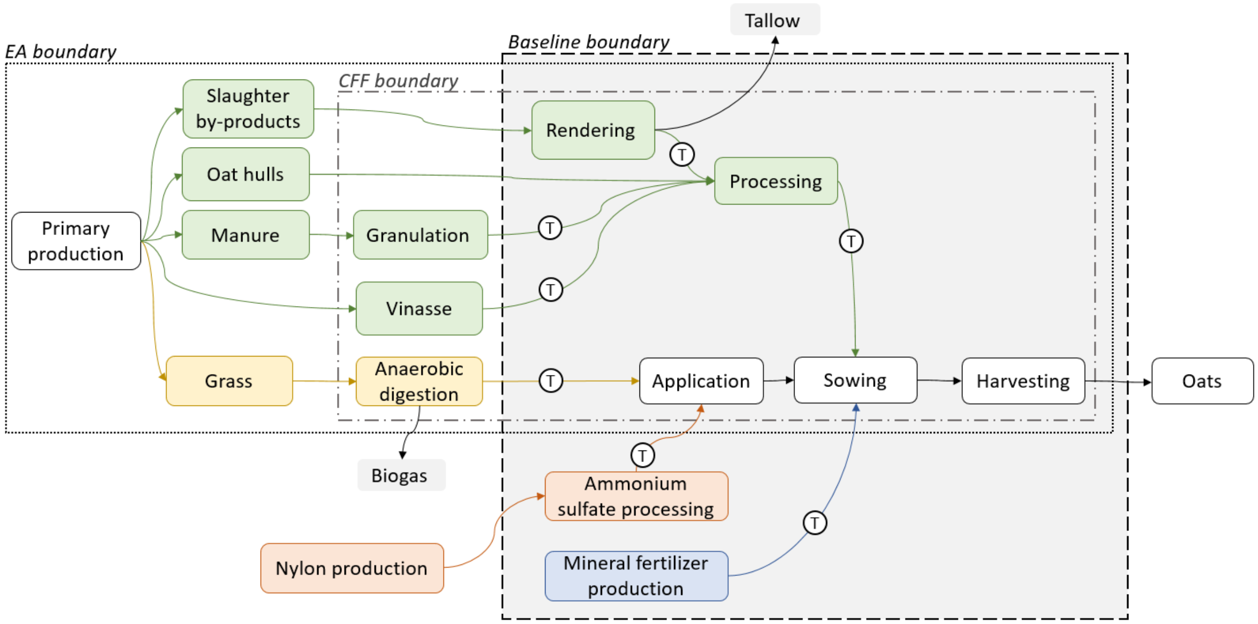

Figure 1. System boundaries for different fertilizers (color codes: Ammonium sulfate = red; Biogas digestate = yellow; Meat and bone meal = green; Mineral fertilizer = blue; applicable to several fertilizers = white) and allocation scenarios: baseline (dashed line), economic allocation (EA, dotted line) and Circular Footprint Formula (CFF, dash-dotted line). T = transportation.

In the baseline system model, the materials of recycled fertilizers were considered to be residues and no burdens or credits were allocated to them. The processing of animal by-products into MBM and fat was allocated between these products based on mass (62% to MBM).

In order to compare the impacts of allocation methods on the results, handling raw materials as products with economic allocation or as wastes with Circular Footprint Formula (CFF) developed by the European Commission's Environmental Footprint project (European Commission, 2018) were tested for BD and MBM. CFF handles the materials as recyclable waste from other systems and thus the materials are not burdened with impacts from system providing the material but impacts from the recycling process and transportations linked to recycling process are allocated between the systems providing and the systems using the material. The processes for which the CFF was applied were for BD anaerobic digestion and for MBM rendering, poultry manure drying and pelletizing, vinasse processing and transportations of these materials. Oat hulls are not processed before use in the fertilizer manufacturing and therefore recycling process for oat hulls was not included.

Following the ISO 14040:2006 allocation procedure, economic allocation was applied when raw materials were handled as products since it can be consistently applied in every stage of the life cycle. A system expansion was considered not applicable since it is better suited for use in consequential models (Pelletier at al., 2015). Also, allocation based on a physical relationship (e.g., mass) was not applied since it is an unequal approach for different uses of the materials.

2.4 Field trials

As the process of manufacturing fertilizers and the raw materials differ greatly, there are also considerable differences in their nutrient contents and application rates. The values presented in Table 1 were used as the basis for the LCA calculations as they were used also in the field experiments. In the field experiment carried out by the Department of Agricultural Sciences at the University of Helsinki, the fertilizer application rate and the method were chosen by the company manufacturing the recycled fertilizer following their best available practices. All the operations were controlled, managed, and executed by the scientists and technicians of the university.

In addition, the mineral fertilizer was tested with two different N application rates (MF 107 & MF 160, see Table 1), MF 160 being the maximum amount of N for oat permitted by law (VN, 2014). The mineral fertilizers were purchased from an agricultural supplier, and the application rates and methods were designed by the university's scientists, following the best available practice and recommendations of the fertilizer company. Also, a zero control (Z) with no fertilization was included in the field experiments.

The BD treatment included also the recycled fertilizer product "Combooster" (2% of the total amount of fertilizer applied), which was included in the nutrient content of fertilizer treatments. The nutrient concentrations shown in Table 1 are based on the concentrations reported by the manufacturer or retailer (Lantmännen Agro, 2019; Soilfood, 2018; Yara, 2020).

Table 1. Application rates and the concentrations of the main nutrient in fertilizers. Mineral fertilization was studied with two application rates. AS = ammonium sulfate; BD = biogas digestate; K = potassium; MBM = meat and bone meal; MF = mineral fertilizer (N ha^{-1}); N = nitrogen; P = phosphorus.

Fertilizer	Application rate kg ha^{-1}	Nutrient concentration %			N applied kg ha^{-1}
		N	**P**	**K**	
AS	571	21	–	–	120
BD	20 180	0.65	0.04	0.4	130
MBM	901	8	4	2	68
MF 107/160	399/599	26.8	–	1	107/161

Spring sown oat cultivar "Obelix" yield trials were carried out as field experiments during the growing season 2017 in Haltiala farm (in Helsinki; soil type silty loam, organic matter content in class 6–12% w/w; at start of the experiment no nutrient deficiencies but relatively low manganese and boron; no significant differences in soil properties between the treatment plots).

Spring sown cultivars of small grain cereals dominate in Finnish cereal production due to short growing seasons and extreme overwintering conditions. As in conventional practice for spring sown cereals, the fertilizers were applied in spring at sowing, except for BD fertilization which was done at the three leaves growth stage (BBCH, 2001).

The experiment was laid out by the project HYKERRYS, studying recycled fertilizers over a five-year rotation. In the field trial of the project, several fertilizer treatments with various fertilizers were tested. The design was completely randomized blocks with four blocks as replicates. The plot size was a minimum 4 m × 8 m (the design allowed for the fertilizer manufacturers to divide their main plot of 8 m × 20 m into four subplots). Only one fertilizer treatment per main plot was included in this study.

In the LCA, the average (n=4) oat grain yield (dry matter content 86%) per plot, obtained by the fertilizer under assessment was used (Figure 2). The arable area required for the production of a ton of oats was calculated on the basis of the kg ha^{-1} yields, which equaled AS 0.18, BD 0.17, MBM 0.18, MF 107 0.15, MF 160 0.15, and Z 0.26 hectare yield t^{-1}. These land requirements were used as the basis for LCA of fertilizer application, sowing, and harvesting per yield ton. The experimental average yield for each fertilizer was used even if there were no statistically significant differences ($P < 0.05$) between the fertilized treatments.

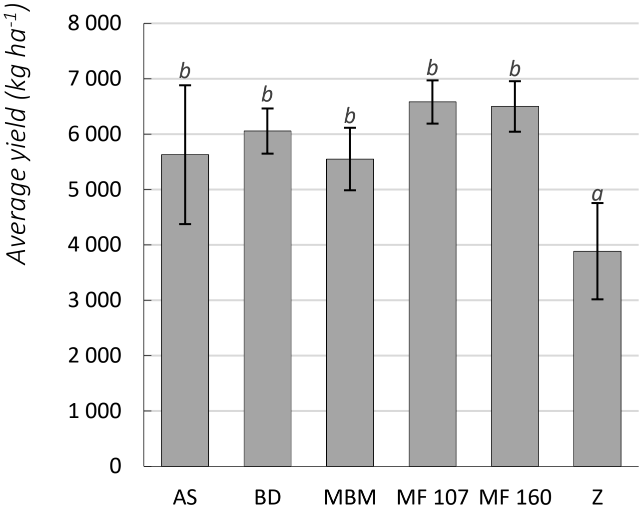

Figure 2. Average oat yields (kg ha^{-1}) attained with different fertilizers from field experiments. Error bars: ± standard error of mean. No statistical significance between treatments associated with the same letter ($P < 0.05$). AS = ammonium sulfate; BD = biogas digestate; MBM = meat and bone meal; MF = mineral fertilizer (N ha^{-1}); Z = no fertilization.

2.5 Energy use and GHG emission data

GHG emissions and energy use were modeled with openLCA 1.10.2 software along with the embedded Ecoinvent 3.6 (2019) database (openLCA; Wernet et al. 2016). Depending on the availability of data, primarily Finnish or European data were used. A detailed description of data is presented in Appendix (A.1).

MBM fertilizer contains 78% meat and bone meal, 8% oat hulls, 8% vinasse and 6% granulated poultry manure (Kivelä, 2019). In the production of MBM-based fertilizer, the electricity and heat consumption in the production of the MBM component were obtained directly from the company (Lehtinen, 2018). The processing results 26% of raw material to MBM and 16% to fat. Also, the transportation of meat and bone meal (100 km), vinasse (200 km), and chicken manure (1850 km) to the fertilizer factory was calculated based on the information about transport distances obtained from the fertilizer company (Lehtinen, 2018). The oat hulls used in the fertilizer come from the vicinity of the factory, so their transportation was not included. In calculations of the pelletizing of the fertilizer, the energy consumption of pelletizing large livestock feed was used when the pelletizing phases were mixing, pelletizing, and cooling (Dabbour et al., 2015).

The information concerning the production of AS is based on the production of AS as a by-product of nylon production. The application of AS is assessed according to data concerning liquid application with a field sprayer, a working width of 18 m, and application of BD by vacuum tanker with 5 000l carrying capacity.

For the mineral fertilizer, only the primary nutrient production, calcium ammonium nitrate and potassium, were included. From the Ecoinvent database, European data were used for calcium ammonium nitrate and global data for potassium.

All transports of fertilizers and raw materials were assumed to be freight transport by road. For sowing, the same values were used for all fertilizers; for the empirical data, the sowing technique and effort were the same for all the fertilizers. Also, fertilizing simultaneously with sowing was not considered to increase energy consumption or emissions.

Soil emissions were calculated according to the IPCC Guidelines for National Greenhouse Gas Inventories Tier 1 (IPCC, 2006). In estimations of direct soil emissions, the annual direct N_2O–N emissions from N inputs were included. Estimations of indirect emissions included N_2O–N emissions from the atmospheric deposition of N volatilized from managed soil and from possible leaching and runoff. The formulas and values used are presented in Appendix (A.2).

2.5.1 Economic allocation scenario

Scenarios with broader cradle to farm gate system boundaries were assessed, since the raw materials of fertilizers can be considered as products to which upstream impacts from primary production are allocated.

The economic allocation scenario for BD was modeled based on Ecoinvent data concerning biogas production from grass. The feedstock was assumed to have same nutrient content as the digestate in baseline scenario. No mass loss from feedstock during the biogas process was considered. Economic allocation was calculated based on the N content of digestate, with N price of €1.13 kg^{-1} (Timonen et al., 2019). This resulted 4.3% of impacts being allocated to digestate.

Meat and bone meal was assumed to be half cattle and half swine origin. General global animal production data from Ecoinvent was used. The proportion of nonedible by-products were set to 30% from swine and 55% from cattle (Gac et al., 2014). Economic allocation for cattle category 3 slaughter by-products (0.8%) suggested by the Cattle Model Working Group was applied for both cattle and swine by-products (Saouter et al., 2016). Impacts from oat production to oat hulls were assessed based on the mass and economic allocation (0.44%) information for oat mix fraction (Heusala et al., 2020). For vinasse and dried and pelletized poultry manure, data and prices from Ecoinvent were used. A detailed description of the data sources used is provided in Appendix (A.3).

2.5.2 Circular Footprint Formula

For comparison of methodological choices, also the CFF, which is developed to handle waste in Product Environmental Footprint (PEF) studies, was tested (European Commission, 2018).

The CFF is developed for PEF studies to allocate the impacts between systems providing material for recycling and systems using them (European Commission, 2018). Even though there are no Product Environmental Footprint Category Rules (PEFCR) developed for fertilizers, the suitability of the CFF was tested. The point of substitution was set to after raw-material processing, before MBM pelletizing and BD transportation to farm. Between output products of processing, same economic allocation factors as in economic allocation scenario were used. The description of parameters and values used is shown in Appendix (A.4).

The formula consists of three parts; material, energy and disposal. Since this study is a cradle-to-gate study instead of a cradle-to-grave study, parameters R_2, R_3, and E_D are set equal to 0, the resulting energy and disposal formulas being equal to 0 (European Commission, 2018). The following formula was used:

Material: $(1\text{-}R_1)E_v\text{+}R_1\text{x}(AE_{recycled}\text{+}(1\text{-}A)E_v\text{x}Q_{Sin}/Q_p)\text{+}(1\text{-}A)R_2\text{x}(E_{recyclingEol}\text{-}E^*_v\text{x}Q_{Sout}/Q_P)$

In cradle-to-gate studies, two allocation factors (A) of burdens and credits between supplier and user of recycled materials are used, A = 1 as default (all burdens to user) and material-specific A = 0.5 (European Commission, 2018).

2.6 Sensitivity analysis

The impacts of changes in the input values of yield, fertilizer manufacturing, transportation, fertilizer application, sowing, harvesting, and soil emissions on the results were assessed with

Monte Carlo analysis in MS Office 365 Excel. The analysis was implemented replacing the base value with a randomly generated input value between a given range from the base value in 10 000 replications.

The estimated low and high "Obelix" oat variety yields from official variety trials in 2009–2016 provided the yield uncertainty range (Laine et al., 2017). The uncertainty range for transportation, fertilizer application, sowing, and harvesting (fuel use) 40% and soil N_2O emissions 70% were based on coefficients of variation reported in the literature (Williams et al., 2006). The coefficients of variation reported for emissions from mineral fertilizer manufacturing (7%) was applied also for manufacturing of recycled fertilizers due to a lack of fertilizer product-specific data.

The sensitivity of the model to changes in transportation distances was tested by changing transportation distances from 0 to 500 km.

Since the GHG emissions of mineral fertilizer production differs greatly between data sources, also the effect of using different data source for mineral fertilizer production was tested. The Ecoinvent data used in baseline model was switched to GHG emission data of European calcium ammonium nitrate and potassium production presented in Brentrup et al. (2018). Since the GHG emissions in Brentrup et al. (2018) are converted to CO_2 equivalents according the fourth IPCC assessment report coefficients, also baseline results were converted accordingly for comparison in the sensitivity assessment (IPCC, 2007).

3. Results

The energy use and GHG emissions of MF 160 were the highest of all the studied fertilizers per ton of oats and per hectare, but a lower mineral fertilizer application rate (MF 107) resulted in notable reductions (Figures 3, 4). In all cases the GHG emissions of mineral fertilizers were higher than recycled fertilizers. Also energy use per hectare were higher with mineral fertilizers, but per N kg energy use of MBM was highest and per yield ton higher than MF 107. The biggest differences between fertilizers occurred in manufacturing, whereas impacts from other processes were quite similar. Application of fertilizer separately from sowing had very low impacts. For BD there were no impacts from manufacturing, but the share of transportation was substantially higher.

The lowest GHG emissions for yield ton and hectare were achieved with MBM: this was solely due to low application rates, since MBM had high GHG emissions and energy use per N kg. From recycled fertilizers, AS had the lowest energy use per all functional units and GHG emissions per N kg.

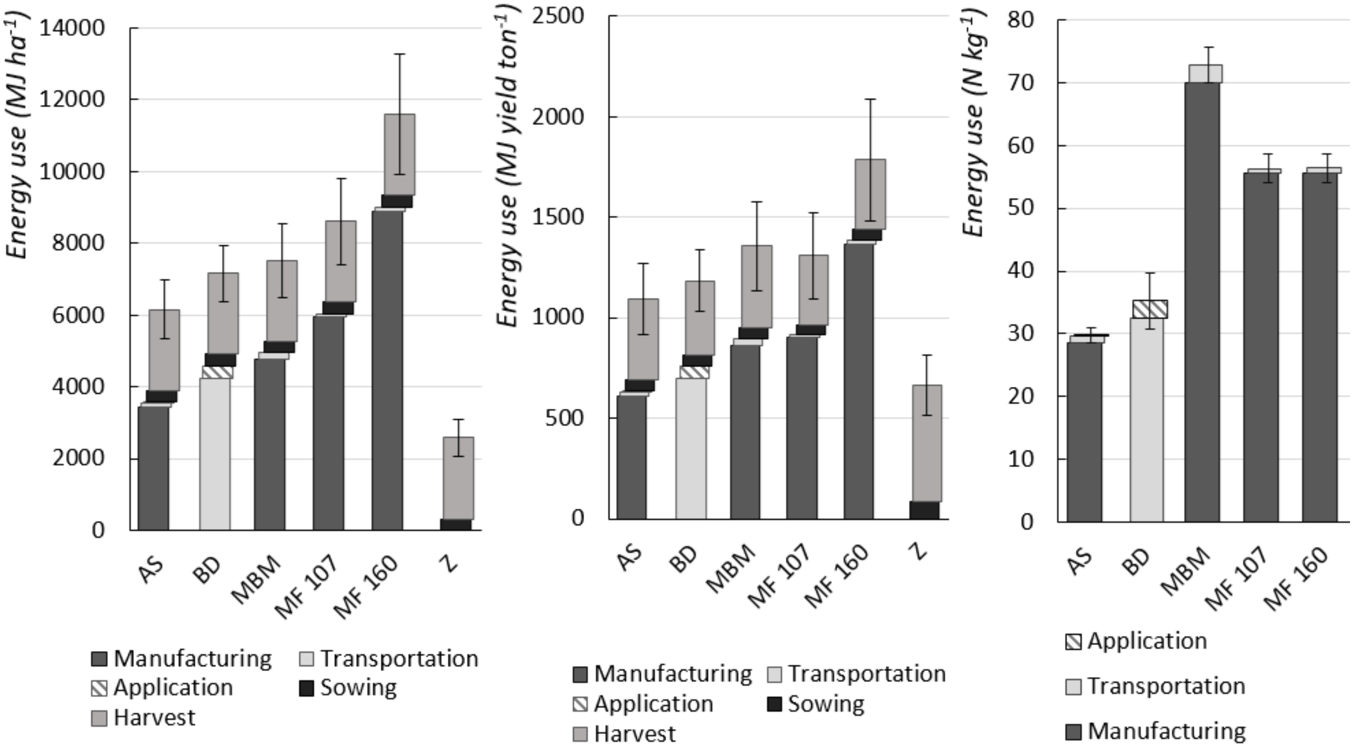

Figure 3. Energy use of different processes in the life cycle of fertilizers per hectare, ton of oat, and kg of fertilizer N (baseline scenario). The error bars represent the ± standard error based on Monte Carlo analysis. AS = ammonium sulfate; BD = biogas digestate; MBM = meat and bone meal; MF = mineral fertilizer (N ha^{-1}); Z = no fertilization.

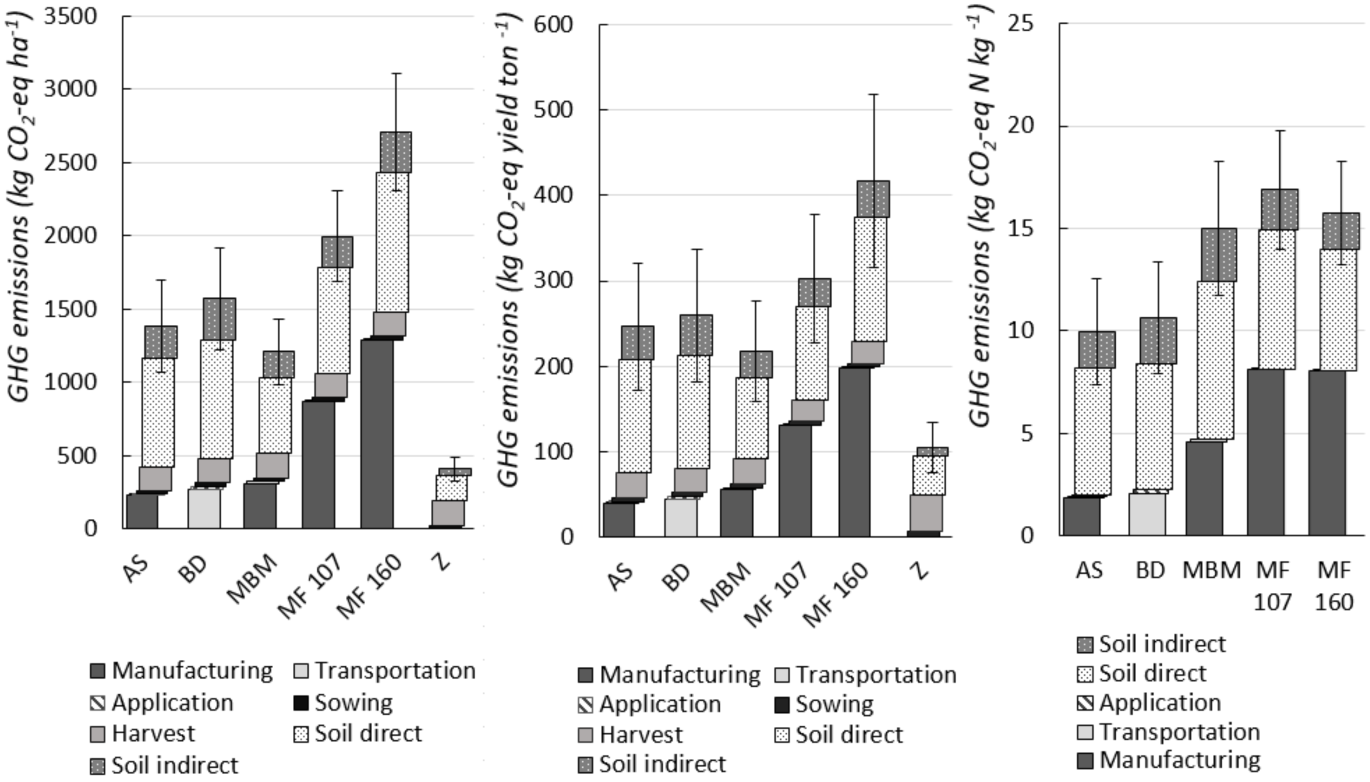

Figure 4. Greenhouse gas (GHG) emissions (kg CO2-eq) of different processes in the life cycle of fertilizers per hectare, ton of oat, and kg of fertilizer N (baseline scenario). The error bars represent the ± standard error based on Monte Carlo analysis. AS = ammonium sulfate; BD = biogas digestate; MBM = meat and bone meal; MF = mineral fertilizer (N ha^{-1}); Z = no fertilization.

Changes in transportation distance significantly affected the BD results due to the low nutrient content and therefore great volume of fertilizer needed (Figure 5). With no transportation at all, the GHG emissions per yield ton of BD and MBM were lowest. As the transportation distance increased, the BD GHG emissions grew rapidly, being greater than MF 160 after 470 km. Changes in transportation distance had only a little effect on other fertilizers.

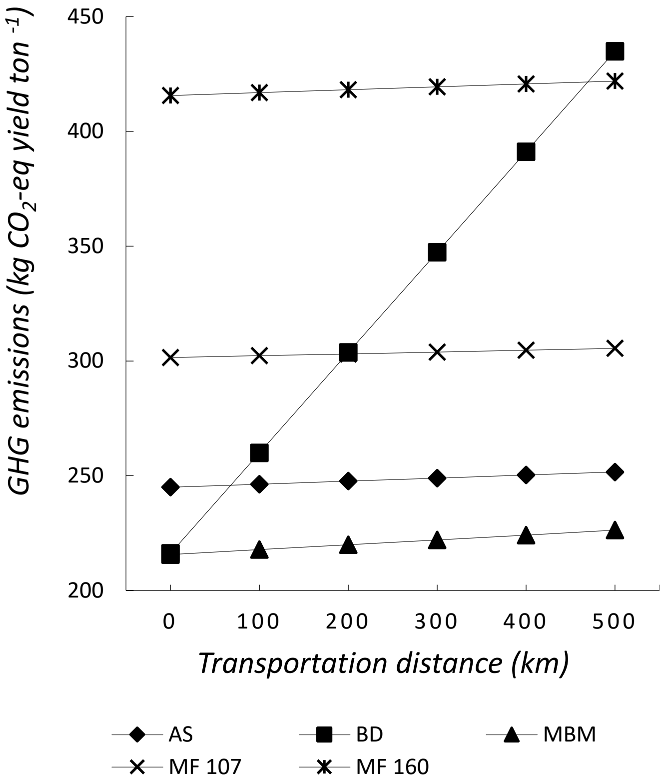

Figure 5. Relation of greenhouse gas (GHG) emissions (kg CO_2-eq yield t^{-1}) to transportation distance of the fertilizer. AS = ammonium sulfate; BD = biogas digestate; MBM = meat and bone meal; MF = mineral fertilizer (kg N ha^{-1}).

The allocation method of raw materials had a significant impact on the results. Handling raw materials as products with economic allocation increased the energy use of BD and decreased the energy use of MBM notably (Figure 6). The GHG emissions of MBM and BD were lower than that of MF 107 with all the different allocation scenarios (Figure 7). Applying economic allocation instead of the mass allocation used in the baseline model for MBM resulted in smaller GHG emissions and energy use. Allocating impacts with CFF led to lower impacts than economic allocation due different system boundaries, but the differences between results of CFF allocation factor 1 and 0.5 were relatively small, except applying CFF (A=0.5) to MBM decreased the energy use per N kg considerably.

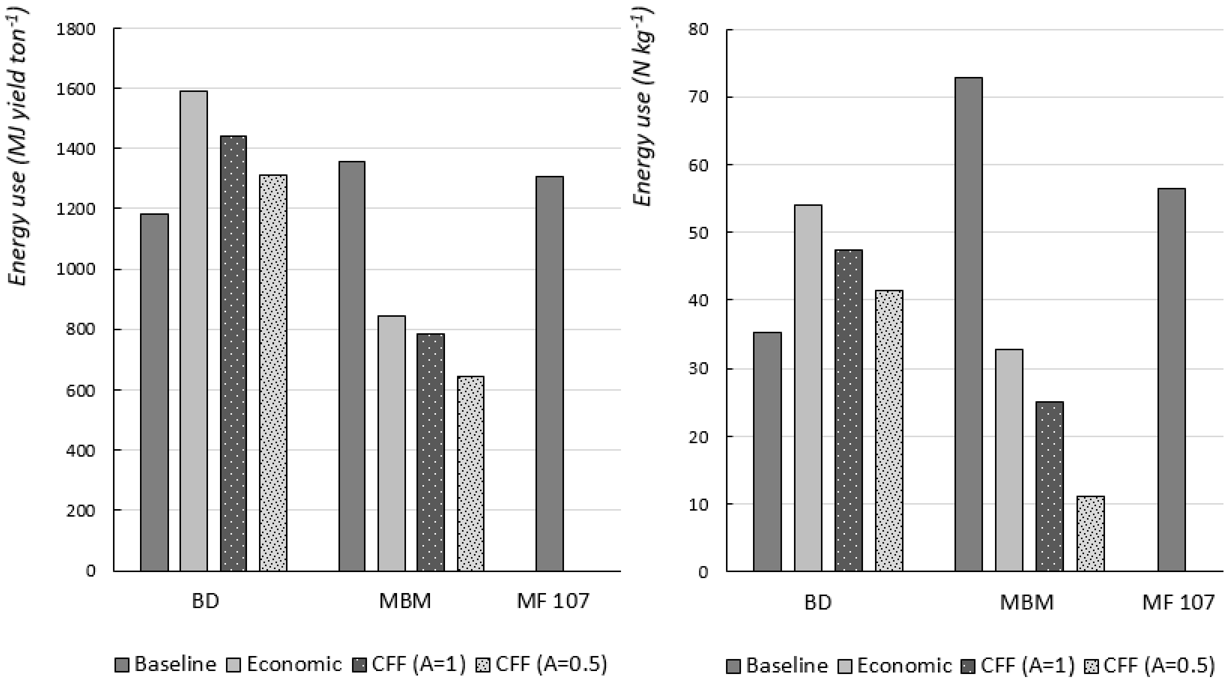

Figure 6. Energy use of fertilizers with different allocation methods. A = allocation factor between supplier and user of recycled materials; A = allocation factor between supplier and user of recycled materials (value 1 = all burden to user); BD = biogas digestate; CFF = Circular Footprint Formula; MBM = meat and bone meal.

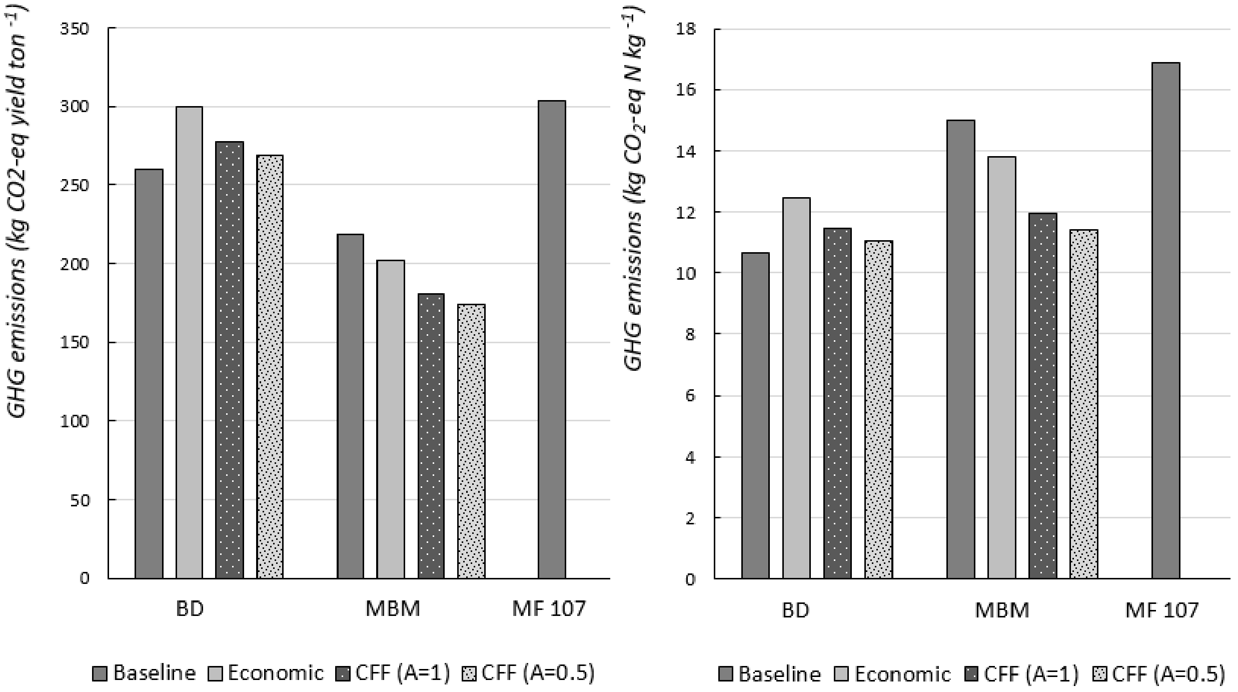

Figure 7. GHG emissions of fertilizers with broader upstream system boundaries and different allocation methods. A = allocation factor between supplier and user of recycled materials (1 = all to user); BD = biogas digestate; CFF = Circular Footprint Formula; MBM = meat and bone meal.

Also the data source has significant impact on results (Fig. 8). Using MF manufacturing GHG emission data provided by Brentrup et al. (2018) instead of Ecoinvent led to around 25% lower GHG emissions of MF per N kg. This results to lower GHG emissions than MBM baseline, but higher than MBM CFF (A = 0.5).

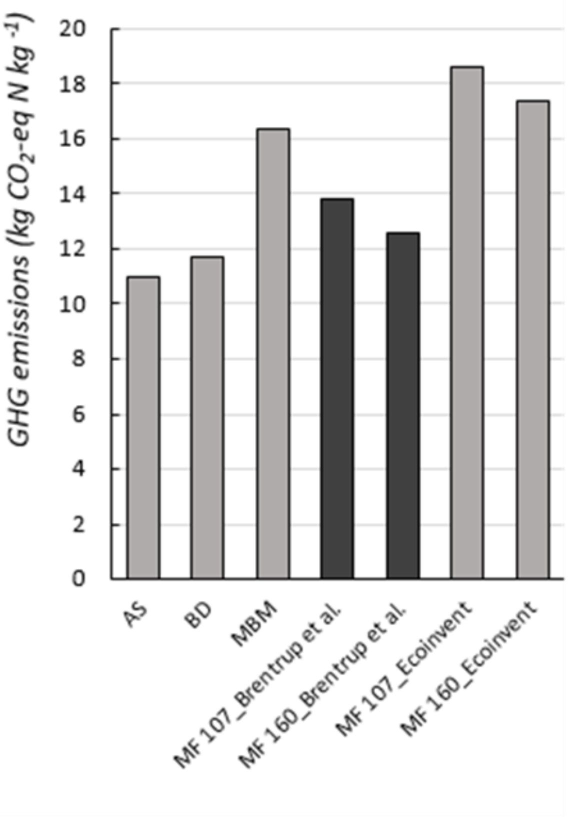

Figure 8. The sensitivity of the GHG emissions of fertilizers (N kg^{-1}) to the data source. Black color represents results when Brentrup et al. (2018) is used as data source for mineral fertilizer production, light gray color represent the baseline results. AS = ammonium sulfate; BD = biogas digestate; MBM = meat and bone meal; MF = mineral fertilizer (N ha^{-1}).

4. Discussion

The growing season was favorable and the yields harvested from field experiments were significantly higher compared with the Finnish average oat yield of 3321 kg ha^{-1} (over the years from 2000 to 2017) but similar to those achieved in the official “Obelix” variety trials in 2009–2016, 6331 kg ha^{-1} (OSF, 2019; Laine et al., 2017). The experimental averages over the plots for the mineral fertilizer yields were somewhat higher than the average yields of the recycled fertilizers, but there were no statistically significant differences in yields of oat between the fertilizers. This is in line with previous studies where mineral fertilization has been found to produce a similar yield as, for example, MBM and BD (Chen et al., 2011; Haraldsen et al., 2011).

Even with higher yields, and hence smaller land use, the GHG emissions and energy use of mineral fertilizer MF 160 were the highest of all the studied fertilizers per ton of oats and hectare, but the lower application rate of MF 107 had significantly lower impacts. The results per yield ton and hectare are quite similar due to low yield differences, unlike the results per N kg, which also indicates the effect of different application rates. High yields achieved regardless of the amount of N applied may be due to already beneficial nutrient status of the soil and therefore it could take several years of similar application rates for the effect of fertilization to be visible. The difference in GHG emissions between MF 160 and MF 107 per N kg is due to soil emissions which are dependent on amount of N applied per land area.

Mineral fertilizers can be manufactured from a variety of components, which affect the energy use and GHG emissions of fertilizers (Brentrup et al., 2018). Also GHG emission data for mineral fertilizer differs greatly between data sources, as the reported emissions per calcium ammonium nitrate N kg are more than double in Ecoinvent database than the newer values reported by Brentrup et al. (2018). This significant difference is due the reference years of the data and the consequent differences in manufacturing technology and efficiency, the principal reference used for the Ecoinvent dates to year 1999 and data presented by Brentup et al. (2018) to 2014. The impact of data source is considerable, increasing the uncertainty of the results and making the comparison of products difficult.

In the life cycle of the BD, transportation was a significant process, because transportation volume was over ten times higher than for the other fertilizers. In previous studies, also storage have been found to be a significant process (Vázquez-Rowe et al., 2015). The savings achieved by not processing the biomass are lost when transportation distance increases, whereas changes in transportation distances have only a little effect on other fertilizers (Figure 5). Since all the transportations were assessed for full loads, the system model might favor BD fertilizer. However, with short transportation distances in localized food systems (e.g., agroecological symbiosis), biogas production has been shown to have the potential to enhance nutrient recycling and crop productivity, and even turn the system energy positive (Koppelmäki et al., 2019).

Recycled fertilizers can also be produced from various side streams or processed in a number of ways, which affects the energy consumption and emissions of the production (Razon, 2012; Vázquez-Rowe et al., 2015). The source of energy used in the manufacture of fertilizers also had a significant impact on emissions, so using different energy sources would have an impact on the results.

In addition to the system boundaries used, the selected allocations also had an impact on the results (Figures 6,7). The method of handling the raw materials of the recycled fertilizers (residue, waste, co-product) affects the system boundaries and the burdens of the raw materials, which broadens the uncertainty of the results. Handling the materials as products results in impacts from primary production being allocated to fertilizers and thus higher impacts. Applying some other method than economic allocation could lead to significantly higher results, since the economic value of materials used in recycled fertilizers is low.

In CFF, the feedstock is handled as waste and no burdens are allocated to feedstock from production, but allocation of recycling process is done between the system producing waste and the system using the waste material. Therefore the results with this method are somewhere between handling materials as product or residue. The allocation of the recycling process can have significant impact on results if the process has high energy consumption, as in the case of MBM.

Different methods have been developed to assess recycling between systems and the credits from displacement effects of material recycling or energy recovery (Allacker et al., 2014). Fertilizer use of organic residues is often assessed by defining the amount of mineral fertilizer substituted (Brockmann et al., 2018; Spångberg et al., 2011). Fertilizer substitutions can be assessed with different principles leading to notable differences in results (Brockmann et al., 2018; Hanserud et al., 2018; Heimersson et al., 2017). Since the GHG emissions of substituting products can vary greatly between data sources, the impact of data source should be taken account also when assessing credits from displacements.

This study did not take into account the environmental savings achieved through the use of side streams, such as avoiding transport to landfills or wastewater treatment plants. The environmental, natural resource, and energy savings achieved by avoiding the use of mineral fertilizers, for example exhaustion of rock phosphate reserves in mining for virgin phosphorus for the industry, have also not been taken into account. Due to these savings, recycled fertilizers are likely to have also consequential benefits.

5. Conclusions

In the light of this study, the life-cycle energy consumption and GHG emissions of recycled fertilizers are generally lower than mineral fertilizer, but differences between fertilizers and different application rates are notable. However, this conclusion is highly sensitive to several decisions, such as data sources and allocation methods used.

Fertilizers that need to be applied in large amounts per unit area are most useful for use only geographically near their production site, but whether the fertilizer requires an application that is separate from the sowing of the crop has only a little effect on emissions or energy consumption. In turn, in the life cycle of fertilizers with less volume but higher nutrient content, the impacts of fertilizer manufacturing are more significant.

Recycled fertilizers can be produced from a variety of side streams and processed in many ways using different energy sources. Further research is therefore necessary to determine the environmental impact of different production methods and fertilizers. To survey all the impacts of avoided processes, a consequential LCA approach should be adopted.

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