

Eco-innovations in the German fertilizer supply chain: Impact on the carbon footprint of fertilizers

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ABSTRACT

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The aim of this paper is to analyse to what extent the existing eco-innovations in the German fertilizer domain might reduce the fertilizer carbon footprint without compromising on crop productivity. The continuously growing demand for agricultural products will require a further increase in agricultural production mostly achieved with additional external inputs (fossil energy, pesticides, irrigation water and fertilizers). Fertilizer in general and nitrogen fertilizers in particular are major factors for yield increases in crop production. On the other hand, emissions of greenhouse gases play a dominant role in the debate on the environmental burden of fertilizers. Typical mineral fertilizers were compared with so-called stabilized nitrogen fertilizers and secondary raw material fertilizers in this study. Additionally, an effect of the combination of irrigation with fertilization (i.e. fertigation) was investigated. With an adopted life cycle assessment approach focusing on CO₂ and N₂O emission, the carbon footprints of the different fertilizer options were considered. The calculations showed that especially the use of stabilized nitrogen fertilizer reduced the fertilization-related carbon footprint up to 13%. However, because of higher costs or incomplete supply chain relationships, adoption of these innovations is expected to be rather limited in the near future. Fertilizers made from secondary raw materials resulted in similar carbon footprints as mineral ones, but they can help to close nutrient cycles and use by-products of other production processes.

Keywords: global warming; pollution; CO₂ and N₂O emissions; climate change

World food production has rapidly grown during the last decades and now feeds over 7.5 billion people. However, the continuing growth of the global population, coming to a plateau at approximately 9 billion people by 2050, will result in a greater competition for land, water and energy (United Nations 2015). To feed the coming world population, the intensity of the production on agricultural land has to be risen markedly (Hazell and Wood

2008). Concurrent with the recent increase in agricultural productivity, agricultural systems are now also recognized to be a significant source of environmental damage (Pretty and Hine 2001, Tilman et al. 2002).

During the last five decades, worldwide fertilizer consumption has grown approximately fourfold, for nitrogen fertilizers even sevenfold (Pretty 2008). Global data for maize, rice, and wheat indicate

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that only 18% to 49% of the fertilizer nitrogen applied is taken up by crops, while the remainder is lost by runoff, leaching and volatilization or immobilized in the soil organic matter (Cassman et al. 2002). Erisman et al. (2008) estimated that in 2005 approximately 100 Mt synthesized nitrogen was used in global agriculture, but only 17 Mt nitrogen was consumed by humans in crop, dairy and meat products, the rest ending up dispersed in the environment. Furthermore, 12% of the greenhouse gas (GHG) emissions worldwide are related to agriculture (Smith et al. 2007) with 38% coming from the use of organic and mineral fertilizers alone (Wegner and Theuvsen 2010). Overall agriculture is responsible for only 7% of the total GHG emission in Germany, but 78% of the N_2O emissions are stemming direct from agriculture and especially from fertilized soils (Umweltbundesamt 2016). This is confirmed by numerous studies reporting that up to 75% of the total GHG emission in crop production resulted from the use of (nitrogen) fertilizers (Engström et al. 2007, Hillier et al. 2009, Ahlgren et al. 2010). This finding is particularly relevant because N_2O has a 298 higher global warming potential in a 100-year timeframe than CO_2 (IPCC 2007).

To improve sustainability in agriculture without losing the possibility of using mineral fertilizers, an option could be the application of innovative agricultural practices and techniques, further entitled as eco-innovations (Spiertz 2010). Eco-innovations are innovations that aim at improving the production, application or exploring of a product that is novel and which results, throughout its life cycle, in a reduction of environmental risk, pollution and negative impacts of resource use (including energy use) compared to relevant alternatives (Kemp et al. 1998, Rennings 2000, Ekins 2010). Eco-innovations are innovations that reduce the environmental impact and potentially lead to a more responsible application of fertilizers in order to achieve low input/high output farming systems (Hasler et al. 2016).

Numerous eco-innovations have been generated in the agricultural domain in the last decades. However, most of them are still not used at farm level although they might have a high potential in decreasing CO_2 emissions (Renni and Heffer 2010). Based on an intensive survey, Hasler et al. (2016) have already shown that most of these agricultural eco-innovations are not relevant for

in-depth studies in GHG emissions, because of their insignificant market penetration. However, three specific fertilizer eco-innovations with high importance for the fertilizer sector and potential of GHG emission reduction could be identified: stabilized nitrogen fertilizers (SNF), fertigation (FG) and secondary raw material fertilizers (SRMF).

One procedure to estimate to what extent the eco-innovations might decrease the amount of GHG emissions related to fertilization is the calculation of the so-called 'carbon footprint'. Rees (1992) was the first who presented the concept of 'ecological footprinting'. In further studies, Wiedmann and Minx (2008) specified this approach by calculating a 'carbon footprint' to quantify the impact of CO_2 emission. However, their approach did not consider N_2O emissions, which are highly associated with the GHG emissions of farming. In 2014, Germany produced in total more than 66 million tons CO_2 equivalents with 30.7 million tons CO_2 equivalents stemming from N_2O emissions (Umweltbundesamt 2016). Therefore, the carbon footprint calculations were extended to a basic life cycle assessment (LCA) approach focusing only on CO_2 and N_2O emissions. Methane emissions were not considered because they mainly occur during rice cultivation, in short-term waterlogged soils and from ruminant livestock (Snyder et al. 2009), and are not relevant for the study on the German fertilizer supply chain.

Additionally, this study uses data on market shares, market penetrations and prices to evaluate to what extent these eco-innovations already lead to improvements in the existing agricultural supply chain. For the following reason, prices, cost structures and the fertilizer supply chain were relevant in our considerations. Farmers are just paying 5–10% of the total variable costs for fertilizers, but especially in the last couple of years the volatility of fertilizer prices increased clearly (Huang 2009), and the availability of certain products for farmers changed significantly, making purchase decision for fertilizers even more difficult. Emissions to the environment provide a further loss of value, which should be avoided. The carbon footprint used as an eco-label for a fertilizer additionally could be a tool to help farmers with purchasing decisions, even though numerous studies with consumers showed, that labelling GHG emission or carbon footprints does not influence the purchasing decisions (Gadema and Oglethorpe 2011, Vanclay et al. 2011).

The motivation for the present study was to identify alternatives for mineral fertilizers with lower GHG emissions to reduce the carbon footprint of fertilization. The remainder of the paper is structured as follows: first, the three selected eco-innovations are briefly described and their possible reduction in GHG emission is explained; next, the carbon footprint calculations and the databases are explained, followed by the results of the carbon footprint calculations including a sensitivity analysis for the input data and the supply chain analysis; finally, the recommendations for farmers, opinion leaders and politicians are discussed.

Studied eco-innovations

Stabilized nitrogen fertilizer. Developed in the 1950's, stabilized nitrogen fertilizers were established to replace multiple applications of nitrogen fertilizer by a single application of a fertilizer that releases nitrogen over a longer time period (Simonne and Hutchinson 2005). In principle, SNF can be manufactured in three different ways: (1) addition of a coating to the granular that builds a physical barrier facilitating a controlled release of the nitrogen; (2) usage of a nitrogen form that is less soluble and therefore needs to be converted to a more soluble, plant available form (sometimes also called 'delayed release') or (3) supplementation of urease and/or nitrification inhibitors (NI) that chemically block or at least delay the transformation of urea/ammonium nitrogen into nitrate nitrogen (Trenkel 1997). Our carbon footprint calculations focus on the last mechanism, because nitrogen fertilizers supplemented with these inhibitors are already used by German farmers.

In several studies, it was shown that the application of SNF reduced in particular gaseous N_2O and slightly also CO_2 emissions (Weiske et al. 2001, Zaman et al. 2008). The reduction of GHG emissions is especially important, because the carbon footprint of agriculture is mostly linked to the direct emission regarding the use of nitrogen fertilizers (Bellarby et al. 2008, Brentrup and Pallière 2008).

Due to climate change (e.g. higher soil temperature, heavy rainfall leading to anoxic soil conditions; Schönthaler et al. 2015) the circumstances for N_2O production in soils after fertilizer application are

more favourable leading to increased N_2O fluxes (Jambert et al. 1997, Hao et al. 2001, Scheer et al. 2008, Aguilera et al. 2013a). Therefore, it might be even more important to use stabilized nitrogen fertilizer products to avoid undesirable gaseous or leaching losses to the environment.

Fertigation. Application of soluble fertilizer together with the irrigation water is defined as FG (Kafkafi 2008). This technology was initially developed in the 1970's in Israel (Goldberg and Shmueli 1971). As nutrients are applied in a water-soluble form, they are immediately accessible for plant uptake right after application, allowing the farmers a greater control over nutrient availability for the crop (Hagin and Lowengart 1995).

FG has two benefits: (1) reduction of fertilizer and water needed for crop production and (2) nutrient application can be scheduled at the precise times they are needed (Bhattarai et al. 2004, Kafkafi 2008). With the combination of these two mechanisms a reduction of N_2O emissions is feasible. Based on the predicted increase of drought periods in some areas in Germany (particularly in summer, Schönthaler et al. 2015) a more widespread use of irrigation systems can be assumed.

Secondary raw material fertilizers. Basic materials which might be used as a fertilizers substitute could come from so-called 'secondary raw materials', such as sewage sludge, compost, organic substances like horn meal, crop residues or various non-usable leftovers from food production. These kind of products must be differentiated from farm-based organic fertilizers (e.g. manure, slurries) or fermentation residues from biogas production. However, these non-farm based products must comply with the German fertilizer regulation (DüMV 2012), which restricts the use of bone meal, meat meal, animal meal and blood-based products (e.g. no application on vegetable or malting barley crops). Such SRMF products are expected to gain more importance when non-renewable raw materials like rock-phosphate become scarce and regulations regarding the closing of nutrient cycles become legally binding. Additionally, plant-based SRMF like leguminous crops meals can help to achieve a balanced nutrient input-output for organically managed farms with low or no livestock. Furthermore, new filter or cleaning technologies (de-Bashan and Bashan 2004) might lead to an increased use of the above-mentioned materials as alternative fertilizer products.

METHODS

General framework for the carbon footprint calculation. To calculate the carbon footprint the definition of Wiedmann and Minx (2008) was used. They outlined that the carbon footprint is the total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. While many of these early carbon footprint assessments only focused on CO₂ emissions, our calculation were extended to a life cycle assessment (LCA) calculations based on the ISO standard (ISO International Standard 14040, 2006) including CO₂ and N₂O emissions. Because our carbon footprint calculations were focused on the German supply chain predominantly for mineral fertilizers, methane emissions were not relevant (Snyder et al. 2009). Contribution to global warming was calculated using the global warming potential for a 100-year time horizon (IPCC 2007) with one CO₂ equivalent for CO₂ and 298 CO₂ equivalents for N₂O. For the carbon footprint calculations an application of 125 kg N per hectare via mineral fertilizers was assumed as an average rate for broad acreage crops in Germany. Our carbon footprint calculations include the mining of raw materials and the extraction of the nutrients from these materials, transportation of raw materials and pre-products, manufacturing of mineral fertilizers, all transportation processes of the final fertilizers to the different market places, application of the fertilizer and the related field operation and finally all emissions during one cultivation period. An empty return trip for trucks was only assumed at agro-dealer and farm level. Emissions from capital goods, buildings as well as from the production of machinery were not included in the calculations, since previous studies revealed that these sources have only little impact on the end results (Baumann and Tillman 2004, Ahlgren et al. 2008).

Transportation. Since fertilizers are both produced within Germany and imported from other regions, a mixed transportation (ship 35%, train 35% and truck 30%) over a mean distance of 700 km was assumed for all mineral fertilizer products applied in German agriculture. Additionally a 100 km transport via truck and tractor (including a return trip) was taken into account for the fertilizer purchase and field operations. All data on emissions for the transportation operations were extracted

from the ProBas database (Umweltbundesamt and Öko-Institut 2016).

Mineral fertilizer production. Basic data for the GHG emission of mineral fertilizer production and application were taken from Davis and Haglund (1999), Jenssen and Kongshaug (2003), Wood and Cowie (2004), IPCC (2007), Snyder et al. (2009) and Hasler et al. (2015). The flow-chart of the mineral fertilizer production and input materials is shown in Figure 1 (EFMA 2000a–d).

Due to new production technologies, N₂O emissions have been drastically reduced during the last decade especially in European fertilizer plants (up to more than 90%; Jenssen and Kongshaug 2003, Brentrup and Pallière 2008). Because mineral fertilizers are produced and traded with a worldwide trading network, it was assumed that for the nitrogen fertilizer mix offered in Germany, less N₂O is emitted during the production process. An average value of 70% was used for the N₂O emissions compared to the values listed in the above-mentioned publications, leading to an N₂O emission of 0.000036 kg per kg urea and up to 0.00116 kg per kg CAN.

Emissions from mineral fertilizer during crop cultivation. To estimate the N₂O emission during field cultivation, emissions from mineral fertilizers applied to a crop during the cultivation period with an emission factor of 4.65 kg CO₂ per kg applied nitrogen were used (IPCC 2007). Additionally, an average of about 3.6 kg of lime per ha had to be applied for each kg nitrogen to balance the acidity resulting from nitrogen turnover in soils and

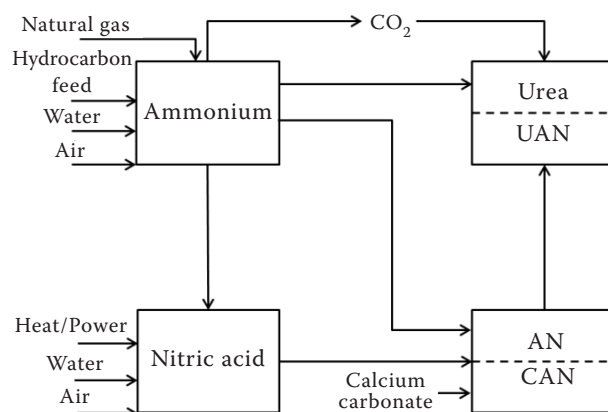


Figure 1. Flow-chart of mineral fertilizer production with natural gas as feedstock. UAN – urea ammonium nitrate; AN – ammonium nitrate; CAN – calcium ammonium nitrate

nitrogen uptake by plants (Snyder et al. 2009). Application of lime results in an average addition of 0.234 kg CO₂ emission per kg limestone according to the IPCC Tier 2 methodology (IPCC 2007). This amount of lime results in an additional GWP of $3.6 \times 0.234 = 0.84$ kg CO₂ per kg of nitrogen applied.

When producing urea, CO₂ reacts with NH₃ to form the urea molecule (CO(NH₂)₂) resulting in a negative carbon footprint (i.e. atmospheric CO₂ is fixed). However, after field application this CO₂ is released after hydrolysis of the urea molecule (Davis and Haglund 1999). Since urea contains 12 g C per 28 g nitrogen, this works out to a GWP of 1.6 kg CO₂ per kg of urea-nitrogen applied. This source category is included because the CO₂ removal from the atmosphere during urea manufacturing is estimated in the Industrial Processes and Product Use Sector (IPCC 2006, Snyder et al. 2009).

Furthermore, indirect N₂O emissions (kg) from nitrogen leaching/runoff were estimated with the following equation (IPCC 2006):

$$N_2O = (F_{Fert} \times Frac_{Leach} \times EF_2) \times \frac{44}{28}$$

Where: F_{Fert} – annual amount of mineral or organic fertilizer nitrogen applied in kg nitrogen per year; $Frac_{leach}$ – fraction of all nitrogen added to or mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff in kg nitrogen per kg of nitrogen additions (for tempered farming environments: 0.3; IPCC 2006); EF_2 – emission factor for N₂O emissions from nitrogen leaching and runoff in kg N₂O-N per kg nitrogen leached and runoff (for tempered farming environments: 0.0075; IPCC 2006).

Stabilized nitrogen fertilizer. Overall, the production of SNF is not different to the production of other mineral nitrogen fertilizers with the exception that during the production process one coating step or the addition of delaying materials (e.g. nitrification inhibitor) has to be considered. It is assumed that the production of these materials takes place at the same site where the fertilizers are produced, so for the carbon footprint calculations only the extra energy and materials were taken into account. Two different additives for stabilizing nitrogen fertilizers were considered: (1) an urease inhibitor (UI; Agrotain), which delays the transformation of urea into ammonium and (2) a nitrification inhibitor (NI; dicyandiamide), which delays the transformation of ammonium into nitrate. Dobbie and Smith (2003), Zaman et al. (2008) and Sanz-Cobena (2012) investigated the effects of UI and of a double inhibi-

tor (UI + NI) on the N₂O emission following urea application in perennial field studies. According to these studies, the application of urea with UI alone reduced the N₂O emissions during the cultivation period by 4.1%, while the use of both inhibitors lowered emissions even by 19%. As expected, the addition of these inhibitors had no reducing effect on the CO₂ emission. Weiske et al. (2001) examined the CO₂ and N₂O emission of ammonium sulfate nitrate (ASN) combined with NI. In this field study, the N₂O emission were reduced by 37%, and the CO₂ emissions by 7%. Data from these field studies were used because they covered more than one cultivation period with different crops, as Brouwman et al. (2002) pointed out that the period covered by the measurements strongly determines the amount of fertilizer nitrogen lost as N₂O.

Fertigation. For the GWP assessment of FG a similar data set was used as for standard mineral fertilizers in combination with emission data of Abalos et al. (2014), Kennedy et al. (2013) and Scheer et al. (2008), who measured GHG emissions in field experiments cropped with several horticultural plants (melons, tomatoes, wine and alfalfa) during various cultivation periods. On average, FG reduced N₂O emissions leading to a lower N₂O emission factor (0.8–0.9% N₂O per kg N applied) for FG, which seems to be a better fit compared to the 1.25% given by the IPCC (2007). Unfortunately, only very few field studies have been conducted focusing on CO₂ emissions due to fertigation. Abalos et al. (2014) reported that the CO₂ emission during field cultivation with melon plants was enhanced by 9% for urea and 39% for calcium nitrate (CN). All emission data were additionally compared with ammonium nitrate (AN) in FG. These data were gathered from a meta study comparing different irrigation systems (drip, furrow, rainfed) in Mediterranean climates (Aguilera et al. 2013b). Production of the irrigation equipment and its transportation was not taken into account, because it was assumed that FG only takes place in regions where irrigation is a standard measure in all cultivation systems.

Secondary raw material fertilizers. For SRMF, the study focused on feather meals, meat and bone meals and leguminous crops meals (Table 1). Compost, sewage sludge or other similar biosolids were not considered because of their rather low nitrogen content and their very poor short-term nitrogen availability.

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Table 1. Characteristics of the secondary raw material fertilizers products considered for the carbon footprint calculation (based on the data from Choi and Nelson (1996), Gutser et al. (2005), and Hartz and Johnstone (2006))

Basic material	Nitrogen content (kg N/t)	Short-term MFE ¹ (%)	Biodegradability of organic matter
Feather meals	120–140	50–70	high
Meat and bone meals	75–125	60–80	very high
Leguminous crops meals	40–60	35–45	high

¹MFE – mineral fertilizer equivalents according to Gutser et al. (2005)

The calculations for the three different SRMF materials were based on data extracted from the ProBas database (Umweltbundesamt and Öko-Institut 2016).

Feather meals. As a starting point for the calculations the production of fattened chicken and their transportation to a slaughterhouse were taken into account. It was presumed that the use of feathers as fertilizer is seen as a valuable alternative to waste disposal, but that only short transport distances are acceptable. A fattened chicken was expected to weight 1.75 kg with 8–10% feathers (0.16 kg) (Latshaw and Bishop 2001). To produce 1 kg chicken meat emissions of 2.4 kg CO₂ and 0.0245 kg N₂O were assumed (Umweltbundesamt and Öko-Institut 2016). The production of the feather meal was assumed to take place in a factory within a maximum distance of 100 km to the slaughterhouse. As process power the German electricity mix of natural gas (11.9%), hard coal (18.1%), nuclear power (15.2%), brown coal (23.9%), renewable energies (26%) and an additional of 4.9% not further categorized, was taken into account (Umweltbundesamt 2016). Finally, the production of one kg feather meal resulted in the emissions of 0.135 kg CO₂ and 0.001375 kg N₂O. Furthermore, transportation of the feather meals to farmers and application in the field (150 km mixed transporta-

tion with trucks and tractor) was included. Finally, it was assumed that the produced feather meal has an average nitrogen content of 130 kg per ton. However, in the year of application only a certain amount of this organically bound nitrogen will be mineralized into plant available N forms. Based on data from Gutser et al. (2005) this so-called ‘mineral fertilizer equivalent (MFE)’ for feather meals can be estimated to 60% of the total applied N. Therefore, 1600 kg feather meal is needed to replace 125 kg nitrogen.

Meat and bone meals. The German meat production of 8.3 million tons is comprised of 67.5% pig, 18% poultry and 14.5% beef. Other meat products (e.g. from sheep, rabbits or ducks) were not taken into account. It was assumed that animal meat is mainly produced for human consumption and only the wastes and residues (e.g. bones, cartilage) were used for the meat and bone meal production. It was also assumed that the residues of the meat production of different animals (pig, poultry and beef) in Germany result in 2.17 million tons (Table 2). As a consequence, only the emissions related to the residues and not to the meat for human consumption were taken into account resulting in 0.56 kg CO₂ and 0.0027 kg N₂O per kg of ready to use meat and bone meals. The production was assumed to take place in Germany or bordering

Table 2. Meat production capacity, production for human consumption, residues and its CO₂ and N₂O emissions for meat and bone meals production in Germany (based on the data from Umweltbundesamt and Öko-Institut 2016)

	Production capacity in Germany	Meat production for human consumption ¹	Production residues	CO ₂ emission from residues	N ₂ O emissions from residues
	(kg/year)				
Pig	6 720 000	5 600 000	1 120 000	300 160	772
Poultry	1 950 000	1 500 000	450 000	206 550	1086
Beef	1 800 000	1 200 000	600 000	720 000	4080
Meat and bone meals	–	–	2 170 000	1 226 710	5938

¹BMEL (2016)

states. GHG emissions of meat production can be found in Table 2. As process power, the German electricity mix (see above) was taken into account.

Additionally, transportation processes along the meat supply chain (farm → slaughterhouse → meat and bone meal production site → field application) with mixed transportation of trucks and tractors (300 km) were included. For the efficiency of meat and bone meals, it was assumed

that the produced meal has an average nitrogen content of 100 kg N/t and a short term MEF of 80%. Therefore, ca. 1560 kg meat and bone meal is necessary to replace 125 kg nitrogen.

Leguminous crops meals. For field cultivation of leguminous crops, it was assumed that the cultivation of 1 kg leguminous grains (beans, peas or lupines), including all field operations (e.g. tillage, seeding, harvesting, etc.), leads to average

Table 3. Greenhouse gas emission (kg CO₂ or kg N₂O) during the production, transportation and application of mineral fertilizers, fertilizers applied via fertigation and fertilizers made from secondary raw materials in one cultivation period

	N-content (%)	Production			
		CO ₂	N ₂ O	CO ₂	N ₂ O as CO ₂ -eq.
		per kg fertilizer		per functional unit*	
AN	35	1.26	0.00141	452	150
AN + FG	35	1.26	0.00141	452	150
CAN	27	0.98	0.00116	456	160
CN + FG		0.98	0.00341	456	464
UAN	32	1.09	0.00070	426	82
Urea	46	1.42	0.00004	386	3
Urea + UI	46	1.42	0.00004	386	3
Urea + UI + NI	46	1.42	0.00004	386	3
Urea + FG	46	1.42	0.00004	386	3
ASN	26	0.93	0.00561	453	465
ASN + NI	26	0.93	0.00561	453	465
Feather meals	0.13	0.14	0.00140	255	734
Meat and bone meals	0.10	0.68	0.00300	1088	1445
Leguminous crops meals	0.05	0.14	0.00001	850	7

	Transportation			Cultivation		
	CO ₂ per tkm	CO ₂ per functional unit*	CO ₂ per kg urea-N or nitrate N	CO ₂ per functional unit*	N ₂ O per kg fertilizer	N ₂ O as CO ₂ -eq. per functional unit*
AN	0.037	10.5	0.84	105	0.0054	596
AN + FG	0.037	10.5	0.84	105	0.0050	534
CAN	0.049	13.8	0.84	105	0.0042	596
CN + FG	0.048	12.9	0.84	105	0.0028	379
UAN	0.041	11.6	0.94	333	0.0050	581
Urea	0.027	7.90	1.60	446	0.0071	596
Urea + UI	0.027	7.90	1.60	446	0.0068	551
Urea + UI + NI	0.027	7.90	1.60	446	0.0045	364
Urea + FG	0.027	7.90	1.60	446	0.0045	370
ASN	0.034	10.7	0.84	105	0.0041	461
ASN + NI	0.034	10.7	0.84	105	0.0027	367
Feather meals	0.015	25.8	0.84	105	0.0011	596
Meat and bone meals	0.015	24.5	0.84	105	0.0012	596
Leguminous crops meals	0.008	53.8	0.84	105	0.0003	596

*representing an application of 125 kg N/ha. AN – ammonium nitrate; FG – fertigation; CAN – calcium ammonium nitrate; CN – calcium nitrate; UAN – urea ammonium nitrate; UI – urease inhibitor; NI – nitrification inhibitor; ASN – ammonium sulfate nitrate

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emissions of 0.136 kg CO₂ and 0.0000399 kg N₂O (Umweltbundesamt and Öko-Institut 2016). A transportation distance of 100 km (for purchase and field operations via truck and tractor) was taken into consideration as most probably only regionally produced meals of leguminous crops are used as fertilizer. It was expected that the considered leguminous crop meals have an average nitrogen content of 50 kg N/t and a short term MFE of 40%. Consequently, 6250 kg leguminous crop meal can replace 125 kg N.

In Table 3 all emissions of CO₂ and N₂O related to the carbon footprint of all considered mineral fertilizers and fertilizer alternatives can be found. All emissions are calculated for a basic fertilizer application of 125 kg N per hectare and cultivation period regarding all the above-mentioned assumptions.

Sensitivity analysis. To check to what extent some of our estimates used for the carbon footprint calculations will impact the final results, a sensitivity analysis was conducted. It has to be expected that fertilizer production capacity especially in Europe will be reduced and therefore longer transportation distances of fertilizer products to Germany have to be expected in the future. As a second scenario, a further reduction in N₂O emissions during fertilizer production was evaluated. With the use of new catalytic converter and filtering technologies, N₂O emission reduction of up to 90% is possible (Brentrup and Pallière 2008).

Implementation of this best available technique in N fertilizer plants in other regions of the world will reduce the carbon footprint of the mineral nitrogen fertilizer mix applied in German agriculture. Finally, a scenario was evaluated where the MFE is low (smallest number in Table 1) and therefore higher amounts of SRMF products are necessary to compensate mineral fertilizer.

RESULTS

Carbon footprint of mineral fertilizers. Emissions of CO₂ during production and N₂O emissions during cultivation have a high share in the total carbon footprint. On the other hand transportation share is very low (0.5–0.9%). The carbon footprints of the assessed mineral fertilizers vary between 1313 kg for AN up to 1460 kg CO₂-equivalents for UAN (Figure 2). About 56% of the CO₂-equivalent emission for ammonium nitrate-based fertilizer is related to the production, for urea and UAN it is only 30–35%. On the other hand, CO₂ emissions of urea and UAN are much higher during the cultivation period.

Carbon footprint of different stabilized nitrogen fertilizers. The carbon footprint of SNF is in all cases lower compared to the respective nitrogen fertilizers without additives. In case of urea, urease inhibitors seem to be less effective (carbon footprint: 1420 kg CO₂-equivalents) compared to

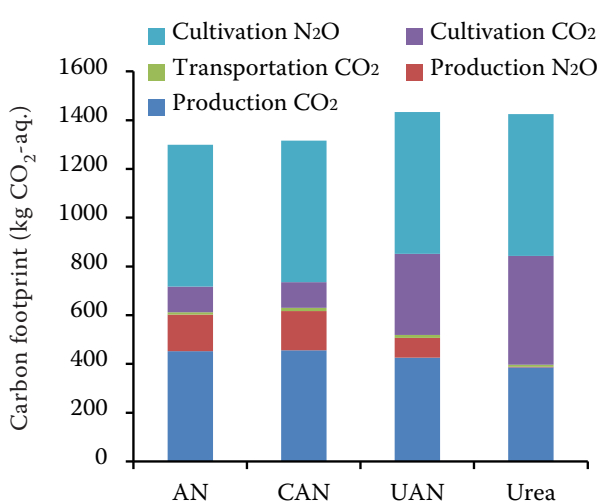


Figure 2. Carbon footprints of different mineral fertilizers calculated for one cultivation period. AN – ammonium nitrate; CAN – calcium ammonium nitrate; UAN – urea ammonium nitrate

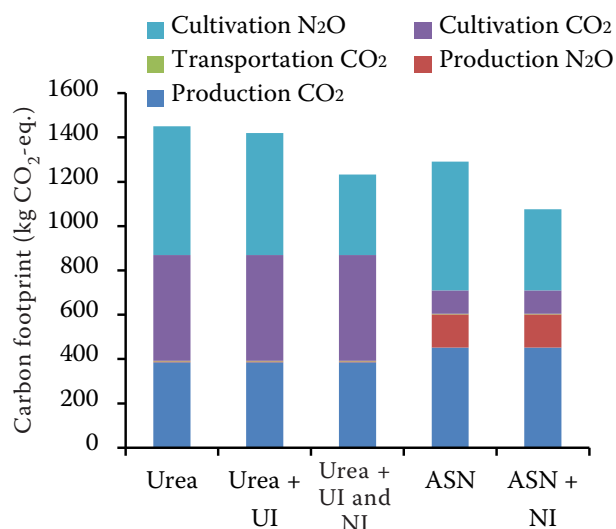


Figure 3. Carbon footprint of different mineral fertilizers and the respective stabilized nitrogen fertilizers products for one cultivation period. UI – urease inhibitor; NI – nitrification inhibitor; ASN – ammonium sulfate nitrate

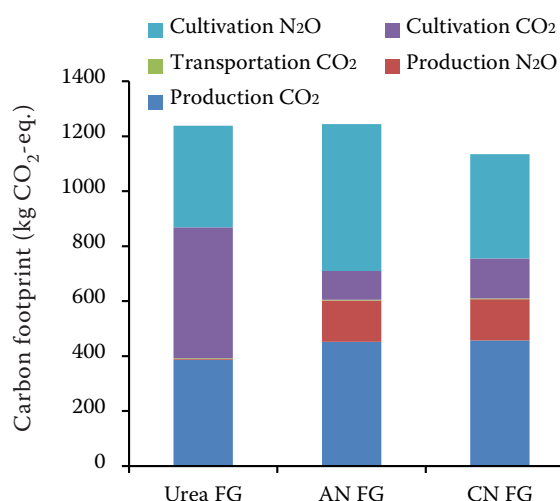


Figure 4. Carbon footprint of different mineral fertilizers applied via irrigation for one cultivation period. CN – calcium nitrate; AN – ammonium nitrate; FG – fertigation

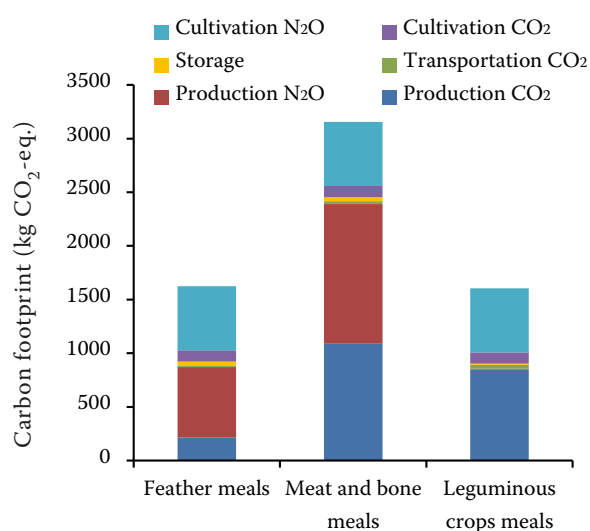


Figure 5. Carbon footprint of different secondary raw material fertilizers

a combination of urease and nitrification inhibitors (carbon footprint: 1340 kg CO₂-equivalents; Figure 3).

Addition of the nitrification inhibitor dicyanamide to ammonium sulfate nitrate reduces the carbon footprint by 17% from 1291 kg CO₂-equivalents to 1076 kg CO₂-equivalents.

Carbon footprint of fertigation. Application of mineral fertilizers via irrigation reduces the carbon footprint of mineral fertilizer only slightly for AN (–4%), but to a greater extent for urea (–20%; Figure 4). Especially N₂O emissions during the cultivation period are lower, while all CO₂ and the N₂O emissions during production are similar to conventional mineral fertilizers.

Carbon footprint of different fertilizers made from secondary raw materials. The carbon footprint of SRMF products is dominated by emission during the basic production process (Figure 5). Especially the upstream chain (animal or vegetable production) leads to high emissions (feather meals: 54%; meat and bone meals: 74%; leguminous crops meals: 53% of the overall emissions). In comparison to the carbon footprint of mineral nitrogen fertilizers (ca. 1450 kg CO₂-equivalents) the carbon footprint calculation for feather meals and leguminous crops meals resulted in 10–20% higher values (1621 kg CO₂-equivalents and 1607 kg CO₂-equivalents). Meat and bone meals result, due to the very high emission during the meat production, in a very high carbon footprint of 3281 kg CO₂-equivalents.

Sensitivity analyses and uncertainty of the carbon footprint assessment. The sensitivity analysis (Table 4) reveals that the changes in transportation distance had only a little impact on the final results. On the other hand, changes in the N₂O emissions during production had a great effect on the carbon footprint of fertilizers, except for urea. For SRMF, changes in the short term MFE resulted in much larger carbon footprints.

DISCUSSION

Emissions due to fertilizer application in crop production significantly influence the carbon footprint of agricultural production. However, essential plant nutrients cannot be substituted by other materials and nutrients exported via harvested products or losses from the soil-plant system (e.g. nitrate leaching, ammonia volatilization, N₂O emission) must be compensated to ensure good crop growth. It has to be kept in mind that due to reduced fertilizer input per hectare in German agriculture, yields will decrease and production elsewhere needs to be increased in order to maintain the world food supply. This might shift crop production into areas that are less suitable and/or lead to land-use change (Ewert et al. 2005), which might have even more negative effects on climate change. The IPCC emission factor was used for our calculations even though several studies showed that N₂O emissions for different fertilizer

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Table 4. Changes (%) in the carbon footprint based on a sensitivity analysis

	Transportation distance (+50%)	N ₂ O emission during fertilizer production (–90%)	Very low short-term MFE (SRMF) ¹
Urea	+1	–2	–
AN	+1	–8	–
Urea UI	+1	–1	–
Urea UI + NI	+1	–1	–
Urea FG	±0	–1	–
AN FG	±0	–7	–
Feather meals	+1	–	+5
Meat and bone meals	+1	–	+18
Leguminous crops meals	+4	–	+19

¹see Table 1. MFE – mineral fertilizer equivalents according to Gutser et al. (2005); AN – ammonium nitrate; UI – urease inhibitors; NI – nitrification inhibitor; ASN – ammonium sulfate nitrate; SRMF – secondary raw material fertilizers; FG – fertigation

sources/types (e.g. urea vs. CAN; Bouwman et al. 2002) may vary substantially. However, these differences are mostly due to soil temperature, soil moisture conditions, application rate, soil pH and crop type and less depending on the fertilizer type itself (Bouwman et al. 2002, Stehfest and Bouwman 2006, Snyder et al. 2009).

In the light of the above statements, a more careful and rational use of nitrogen fertilizers in particular would be a win-win solution, being of agronomical, economical, and environmental benefit (Vitousek et al. 1997, Erisman et al. 2008).

Using SNFs has only a little effect (reduction by 2–13%) on the carbon footprint of mineral fertilization in Germany. However, Watson et al. (1998), Zaman et al. (2008) and Sanz-Cobena (2012) showed that the yield of permanent grassland and maize was significantly increased by using mineral fertilizers upgraded with nitrification inhibitors. This leads to the conclusion, that nitrogen use efficiency is higher when using nitrogen fertilizers upgraded with inhibitors. To really compare SNFs and standard mineral fertilizers, an extension of the functional unit to finished product (e.g. one litre of milk for grassland systems or one kg of maize grain) might lead to a better comparison of the carbon footprint of these two fertilizer products.

Irrigation is mostly applied during summer periods when soil temperature, and due to irrigation also the soil moisture conditions for N₂O production after fertilizer application, are more favourable (Jambert et al. 1997, Hao et al. 2001, Scheer et al. 2008, Aguilera et al. 2013b) and therefore a

strong stimulation of the N₂O fluxes might occur. Adapting nitrogen supply closely to crop nitrogen demand during the vegetation period and thereby lowering nitrogen peaks in the soil might be the most important reason for overall lower N₂O emission via fertigation.

The use of SRMF products originating from leftovers of animal or plant production results in high values for the carbon footprint. Nevertheless, using animal-based by-products as fertilizers finally reduces unavoidable waste. Intensive use of limited raw materials, especially of rock-phosphate, combined with the growing world population can lead to a shortage in availability. SRMF products can be one solution to close this gap. Using products and materials that already exist as residues from other production processes could achieve an added value to agriculture, due to the closing of nutrient cycles. In combination with the modification of the German fertilizer legislation this aspects might become even more important. However, the performance of SRMF products depends on the short-term availability of organically bound nitrogen (expressed as MFE) and therefore on their ability to replace mineral fertilizers. As shown, total N content and MFE of different SRMF varies over a wide range and the mineralization rate of the organically bound nitrogen is rather unpredictably influenced by variable environmental conditions. Consequentially, SRMF should always be tested in a laboratory for its nitrogen content before use. For a farmer it would be valuable to get in addition an indication on the easily mineralizable nitrogen in a SRMF product.

The carbon footprints of all examined eco-innovations (SNF, FG and SRMF) are heavily influenced by GHG emissions during the primary fertilizer production step. Overall 50–60% of all emissions are related to the production of mineral fertilizers with nitrate-based fertilizers showing the highest share. The carbon footprint of SRMF products based on animal residues is more influenced by the primary production steps (about 55%) compared to SRMF made from plant residues. The remaining CO₂ or N₂O emissions are mostly related to emissions from fertilized soils. Only a very small part of the overall carbon footprint (1–3%) is related to transportation and storage processes.

All eco-innovations can, for their specific field of application, decrease the carbon footprint related to fertilization, but all have also significant drawbacks compared to standard mineral fertilization. SNF are much higher in price than standard mineral fertilizers and therefore gaining higher market shares will be unlikely as long as these mineral fertilizers are much cheaper. FG comes with high investment costs, higher fertilizer costs and access to high quality water resources must be guaranteed. However, in dryer areas with obligatory irrigation, it combines two relevant field operations and finally lowers the CO₂ and N₂O emissions. SRMF is an alternative for waste disposal and in addition, nutrient cycles are closed. However, it has to be kept in mind that existing fertilizer supply chains cannot be used as distribution channels for these materials.

To achieve a better market diffusion of the examined eco-innovations, the whole fertilizer supply chain needs to be modified. Due to the fact that all these innovations impact the usual distribution structure, a close and constructive involvement of all actors within the fertilizer supply chain is very important. Additionally, it would be necessary to explore the relationship between innovation adoption and innovation networks in agricultural supply chains to get a better understanding of the innovation adoption at farmers' level. Moreover, knowledge is very unevenly distributed in agricultural supply chains (Morgan and Murdoch 2000, Hasler et al. 2016), and thus education and willingness to change needs to start at the beginning of the fertilizer supply chain, i.e. at producer or trader level.

As long as eco-innovations are more expensive than existing alternatives, prices and costs will play a significant role in the decision-making of

farmers. One idea could be the implementation of CO₂ labels. However, up to now, none of the existing consumer CO₂ labels were successful or led to a higher willingness to pay (Gadema and Oglethorpe 2011). Consequently, other political instruments (e.g. price guarantees, certification) and/or soft regulations (e.g. statements and principles, social norms and values) must step in.

Additionally up-to-date emission data for fertilizer production process would make the whole environmental assessment more precise, because most agricultural studies are still using data collected in the period prior to 2000 (e.g. Davis and Haglund 1999, Jenssen and Kongshaug 2003, Wood and Crowie 2004). This is especially relevant as the European production techniques for fertilizers have been significantly improved during the last decade (IFA 2012), while in most studies, data for the calculation of GHG emission during fertilizer production are either stemming from meta-studies or rather old. New production and filtering technologies could drastically reduce the carbon footprint especially of mineral nitrogen fertilizers. However, up to now this technology is practically implemented only in European fertilizer plants and does not represent the worldwide state-of-the-art. Nonetheless, a great potential for reducing the carbon footprint of agriculture is still very inefficiently used. With up-to-date data, better comparisons between new fertilizer products and mineral fertilizer produced with new technologies would give a more reliable picture of the present agriculture.

Costs and supply chain perspectives. The cost for mineral nitrogen fertilizers is mainly driven by the gas prices in the country of production, because natural gas is the feedstock used in 75% to 80% of all nitrogen manufacturing plants (Fixen 2009). As a result, nitrogen fertilizer prices are very volatile whereby farmers tend to buy more fertilizer at lower prices. The eco-innovations presented in this paper are specialized fertilizer products or application systems that are less volatile in pricing, which might be directly related to the small market penetration. One explanation for the small market penetration are most probably higher costs (SNF and FG) or different sales and supply chain strategies (SRMF).

Overall, SNFs have the highest market share of all eco-innovations considered in our study for Germany, but still they have to be ranked as niche

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products. Because the German fertilizer statistic does not distinguish between standard and stabilized nitrogen fertilizers only estimates are available. About a decade ago it was assumed that stabilized fertilizers comprised only 8–10% of the nitrogen fertilizers used in Europe (Lammel 2005, Shaviv 2005), but legal requirements might have led to a faster adaption rate of this technology. As already mentioned, one explanation for the low market penetration of SNFs in German agriculture is the higher costs related to these products (app. 20–60% more expensive). Furthermore, the availability of these products at trader level is lower compared to other fertilizer products. Additionally, the production of these fertilizer products is much more complex, requires an in-depth technical know-how and a more specialized production factory. This might lead to production places in European countries with higher salaries and ecological standards making the SNF even more high-priced.

For FG the extra costs occur mainly at the farm level. It requires extra capital to buy irrigation equipment and to set up the irrigation infrastructure (500–1000 €/ha; KTBL 2013). To avoid clogging, very good water solubility of fertilizer products used for FG is essential. Consequently, fertilizer products used in FG need to be processed differently, which leads to extra investments in production and therefore finally to higher fertilizer prices for growers. This makes FG only profitable for crops with high margins (e.g. strawberries, tomatoes or herbs) explaining why the market adaption of FG in Germany is rather low. However, assuming that climate change will result in warmer and dryer conditions during the growing period, FG seems to be a viable option for many regions in Europe (Nunes et al. 2008).

Using SRMF bypasses the standard fertilizer supply chain, especially the fertilizer producers who are standing at the beginning of this supply chain. Therefore, it can be assumed that fertilizer producers are not willing to promote these fertilizer materials within the existing supply chain. Additionally, SRMF competes with farm-based organic fertilizers (farm-yard manure, slurry) leading to a low acceptance in agricultural regions with high livestock production (for example north-west Germany). Furthermore, SRMF can only be used in accordance with the German fertilizer regulations concerning organic materials as a base material for fertilizer production or fertilizer usage, which excludes rather cheap

materials like blood, bone and animal wastes (DüMV 2012). Despite of these problems, the basic materials of SRMF are relatively cheap and if distributed regionally it might offer a good contribution to the overall nutrient supply demand in German agriculture.

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