Environmental impact of mineral fertilizers: possible improvements through the adoption of eco-innovations

Kathrin Hasler

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Propositions

1. Eco-innovations in the field of fertilizers can greatly reduce the carbon footprint of crop production.
   (this thesis)

2. Farmers have the lowest knowledge of specific fertilizer eco-innovations within the fertilizer supply chain.
   (this thesis)

3. A life cycle assessment can be a useful tool for a consumer label showing the environmental pressure of a product.

4. A reduction in the use of fertilizers will have a significant positive effect on reducing the carbon footprint of global agriculture.

5. To balance agriculture production and nature, the concept of sustainable intensification should be replaced by the concept of ecological intensification.

6. Research in the field of sustainable development can by definition not be apolitical.

Propositions belong to the thesis, entitled: "Environmental impact of mineral fertilizers: possible improvements through the adoption of eco-innovations".

Kathrin Hasler

Wageningen, 05 December 2017

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Thesis

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TABLE OF CONTENT

1. Introduction

Agricultural production has increased since the green revolution of the 1960s and feeds nowadays over 7.5 billion people (United Nations, 2015). IPCC (2001) and FAO (2012) estimated that nearly 50% of this wide increase in output is mainly based on the increase of fertilizer inputs (**Figure 1-1**). Stewart et al. (2005) who, reviewed data representing 362 seasons of crop production report that at least 30 to 50% of crop yield can be assigned to fertilizer inputs. Continuing world food crisis and population growth indicates a need for substantially greater use of (agricultural) inputs (Cassman et al., 2002; Trewavas, 2002). However, it would be simplistic and optimistic to assume that this correlation will remain linear in the future and that gains will continue at the previous rates (Tilman, 1999). Additionally the global use of fertilizers is very diverse: In North America, Western Europe, China and India overfertilization causes environmental pollution, while in Africa, Eurasia and parts of Latin America a limited application of nutrients causes soil mining (Bindraban et al., 2015). In parallel to the world population growth the caloric intake per capita will increase, too (Bodirsky et al., 2015). That does not only affect the amount of energy (calorie content) but also the protein demand, especially for meat and dairy products, because both are closely bound to the rising prosperity (Tilman et al., 2001). In the future the animal protein consumption is anticipated to increase significantly over the next 20 years in Asia, Latin America, and Africa (Popp et al., 2010; Schönthaler et al., 2015), which will lead to higher consumption of plant materials as animal feed and also higher emissions to the environment (Steinfeld et al., 2006). Furthermore, in many developed countries, enhanced use of renewable resources for energy production is expected. The Europe Union intents to increase the use of renewable resources up to 20% until 2020 (European Union, 2016) putting additional pressure on agricultural bioenergy production. Other driving forces which pressured the agriculture sector to transform are: changes in natural conditions (climate, diseases, flooding), changes in markets and prices, the development and application of new technologies, changes in consumers judgments and governmental policies and measures (Spiertz and Oenema, 2005).

One solution to stop the continuing world food crisis might be the suggestion of a substantially greater use of fertilizer inputs. However, there is growing evidence that fertilizer use has already reached critical environmental limits, and that the aggregate costs in terms of lost or foregone benefits from environmental service are too great for the world to bear (Ruttan, 2002; Kitzes et al., 2007). Agriculture already occupies nearly 50% of the world´s arable land (Foley et al., 2005). Most of the optimum quality farmland is already used for agriculture, which means that a further area expansion will occur on land which is less suited for productive agriculture (Cassman, 1999; Young, 1999; Koning and van Ittersum, 2009). Shifting certain parts of agricultural production to more productive countries, which can be summarized to as sustainable intensification, may be an economically more efficient way to increase overall productivity (Lotze-Campen et al., 2010). Nevertheless, combined with the predicted population growth and the expanding demand for agricultural goods it will constantly increase the pressure on scared land and ecosystems (Challinor et al., 2009; Spiertz and Ewert, 2009; Spiertz, 2010).

With a higher farming intensity the environmental impacts on non-agricultural ecosystems will also increase. Especially the production and application of (nitrogen) fertilizer generate a high amount of greenhouse gas emissions and has high primary energy consumption during the production (Davis and Haglund, 1999; Bellarby et al., 2008; Brentrup and Pallière, 2008). Mineral nitrogen fertilizers comprise almost 60% of the global reactive nitrogen load attributable to human activities (Spiertz and Oenema, 2005). Nevertheless, nitrogen is the most important mineral nutrient for agricultural production and an adequate supply is essential for high yield, especially with modern cultivars (Mulvaney et al., 2009).

Here the implementation of so called environmental or eco-innovations could solve a wide range of the above mentioned problems. Eco-innovations are innovations which not only intent to improve the economic value, but also the ecological value of a product or service (Rennings, 2000). Because of their holistic nature, eco-innovations are facing problems in propagation beyond the normal problems of innovations (Frondel et al., 2008; Horbach, 2008). Therefore, eco-innovations need a specific environment for an extended diffusion. However, the application of eco-innovations could results in agriculture higher in sustainability.

1.1 Challenges to be addressed

Fertilizers are important for a productive agriculture (Tilman et al., 2002; Spiertz and Ewert, 2009). However, these nutrient inputs come with high environmental impacts as well (Mosier and Syers, 2004; Spiertz, 2010). The question remains, where to draw the line in the consideration between human food and energy supply and the environmental impact of fertilizers.

The overall aim of this thesis is to evaluate the environmental impact of fertilization and to obtain a better understanding of the eco-innovation adoption within agricultural supply chains. In order to achieve this, the following set of statements have been developed focusing on different aspects of fertilizer application and innovation adoption:

Research aim
To evaluate and understand the environmental impact of (mineral) fertilizers and the adoption of eco-innovations in the fertilizer supply chain.

To achieve the research aim, this thesis investigates the empirical evidence of sustainability in fertilization with the fertilizer supply chain as supporter of sustainable developments. In doing so, the thesis answers the following main research question:

Main research question
To what extent can the environmental impact of fertilizers be improved by accelerating the adoption and diffusion of eco-innovations within the fertilizer supply chain?

Additionally the main research question was split into the following set of questions which focus on different theoretical perspectives used in this thesis. The first perspective brings the environmental dimension of the fertilization into focus. By regarding the fact, that (mineral) fertilizers will have in some characteristics a negative effect on the environment, it was questioned if there is a potential for reducing these effects without changing the farming management or introducing new fertilizer technologies.

Main research question with an environmental context
To what extent is it possible to reduce the environmental impact of fertilizers without changing the farming management system?

The second more general research question concentrates on the innovation management perspective putting the adoption and diffusion of innovations into focus. Here more general problems of the fertilizer supply chain itself were concentrated by questioning:

Main research question with an innovation management context
How can the diffusion of eco-innovations be improved within the fertilizer supply chain?

To answer these research questions, the research aim was translated into four research objectives that are presented in the Chapters 2 to 5.

The introduction is structured as follows: First the term sustainable agriculture, sustainable use of fertilizers and the concepts eco-innovation and eco-innovation adoption will be defined (Section 1.2). Second the theoretical perspectives with a focus on LCA, carbon footprint, the technology acceptance model and its extension and eco-innovation diffusion were outlined (Section 1.3). In Section 1.4 the fertilizer supply chain in Germany is shortly defined. Finally this chapter concludes with the outline of the thesis (Section 1.5).

1.2 Sustainable agriculture

Sustainability and sustainable development are the dominating paradigm in environmental, economic and ecological literature of the 20th and 21st century (see Lele, 1991; Cash et al., 2003; Redcliff, 2005). The concept has been rapidly adopted by politicians, economists and ecologists and is now encountered in all spheres of life. Although the term is widespread used, the definition is still used in a wide range. One of the most cited definitions of sustainability is '*a development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (Brundtland, 1987). A further definition is the 'triple bottom line' of sustainability, in which environmental, social and financial outcomes are taken into account (Elkington, 1999). Additional there are two different perspectives of when sustainability exists: first when no elements of the system are overloaded (Brown, 2003) and second when the capacity to create, test and maintain the capability of an ecosystem is still given (Holling, 2002).

Today, concerns about agricultural sustainability centre on the need to develop agricultural technologies and practices that (1) do not have adverse effects on the environment (partly because the environment is an important asset for farming), (2) are accessible to and effective for farmers, and (3) lead to both improvements in food productivity and have positive side effects on environmental goods and services (Pretty, 2008).

Agriculture has the responsibility to provide society with high quality food in a long term. Environmental side-effects of agriculture were recognized from the beginning of the 1970ies related to excess use of animal manure, fertilizer, pesticides and irrigation. One of the first definition of sustainable agriculture was published by the American Society of Agronomy (1989*) 'A sustainable agriculture is one that, over the long term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fibre needs; is economically viable; and enhances the quality of life for farmers and society as a whole'.*

From 1985 onwards, a series of environmental policies and measures have been implemented, especially addressing fertilizers use (Spiertz and Oenema, 2005). York (1991) argued that only a few options exist for reducing fertilizer inputs in agricultural systems while maintaining sustainable production. Unlike pesticides, nutrient elements generally have no substitutes and are subjected to harvest and other losses that must be replaced by weathering of soil minerals or imported from outside the system if production is to be sustained.

Agriculture systems high in sustainability can be taken as those that aim to make the best use of goods and services without effecting the capacity of the eco-system (Pretty, 2008). As key principles for sustainability in agriculture the following were defined (Tilman et al., 2002; Pretty, 2008; Uphoff, 2013):

- Integrate biological and ecological processes (e.g. nutrient cycling, nitrogen fixation or soil regeneration).
- Minimize the use of those non-renewable inputs that cause harm to the environment, farmers or consumers.
- Make productive use of the knowledge and skills of farmers and thereby improving their self-reliance and substituting human capital for external inputs.
- Make productive use of people´s collective capacities to work together to solve common agricultural and natural resource problems.

According to IPCC (2001) agriculture accounted for about 3% of the global energy consumption, but more than 20% of the global greenhouse gas emissions. The main emissions are related to livestock and fertilizer production. In the next years both are expected to increase with an increasing world population and income by approximately 20 and 25% (Rabobank, 2011; IFA, 2012). The nitrogen consumption is projected to change 105 Mt (million tons) in 2013 to 80–180 Mt nitrogen per year by 2050. Similarly, the consumption of phosphor could change from the current 40 Mt to 35–70 Mt phosphor per year (Sutton et al., 2013), while potassium consumption, approximating 29 Mt potassium per year, may increase by 1 to 2% per annum (FAO, 2012).

The annual worldwide mineral fertilizer production is 400 billion tones, excluding the Chinese production for their own consumption, because this do not appear in any statistic (Windridge et al., 1998; IFA, 2012). The main energy requirement is linked to the production of nitrogen containing fertilizers. Net energy consumption for the world fertilizer production is approximately 4400 million GJ per year (Jenssen and Kongshaug, 2003). So it is no surprise that the fertilizer price is closely linked to the energy prices in general and to the oil price in particular. That was most visible in the year 2007/2008 when the overall financial crises caused a considerable price increase and a peak rising in commodity prices at the fertilizer sector (Chen et al., 2010). However, nowadays the fertilizer consumption is as high as in pre crises era and is expected to further increase (FAO, 2012; **Figure 1-1**).

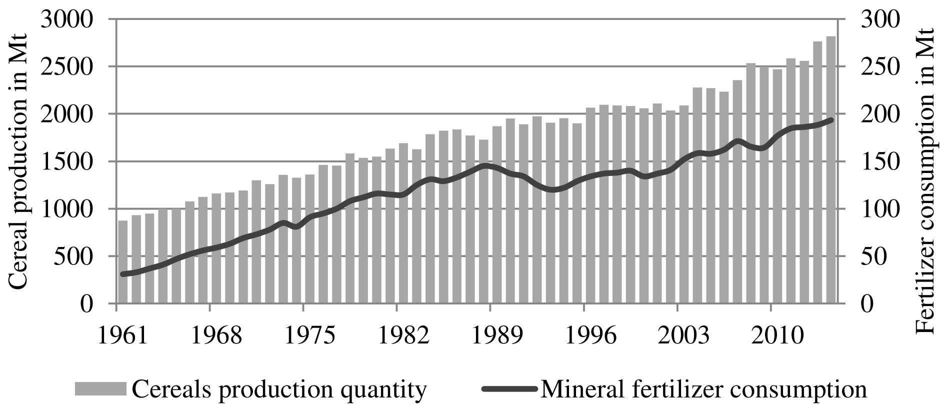

Figure 1-1 World cereal production and fertilizer consumption from 1961-2014 (FAOSTAT, 2017).

Caused by several negative press reports related to the use of plant nutrients (e.g. high nitrate concentration in drinking water or completely oxygen-depleted dead zone in oceans), the use of fertilizer is increasingly questioned by consumers and policy makers (Jackmann, 2003). An increasing awareness of the environmental impacts of agriculture drastically changes the agricultural policies of the EU (Spiertz and Oenema, 2005). In Asia or Africa on the other hand a further intensification of agriculture inputs are observed and intended (Woods et al., 2010). Nevertheless, nitrogen loses to the environment within the fertilizer supply chain is more than twice as high in developing countries (18% of the applied amount) as in the developed countries (7%), because of higher temperatures, major losses during the transportation and storage and the use of different fertilizer types (urea vs. ammonium; Steinfeld et al., 2006). The calculation of the so called nutrient use efficiency, which estimates the nutrient uptake by the plant and the nutrient lost to the environment, is one tool to estimate the effect of fertilization (Vitousek, 1982). The fertilizer nitrogen recovery for example depends on the crop, environmental conditions and management technology and ranges from 35% to 65% for cereals (Herrera et al., 2016a).

The development of fertilizers has mainly been driven by identifying cheap sources of plant nutrients. Although this is essential to produce affordable food, knowledge of plant physiology significantly benefits the development of new fertilizer sources (Bindraban et al., 2015). Valuable lessons could be learned from developments in pesticides over the past decades that moved from toxic, persistent chemicals towards targeted, systemic bio-pesticides based on understanding of the relevant biological processes (Bindraban et al., 2015). Fuglie et al. (2011) estimated that the fertilizer industry invests only 0.1–0.2% of its revenue in R&D, compared to about 10 by the seed sector, respectively. Therefore, given the essentiality of fertilizers to secure sufficient food production, there is an urgent need for revisiting the concept of fertilizers, to reduce its environmental footprint while making them even more economically efficient for resource-poor farmers. Although fertilizer production is energy-intensive, a reduced use of mineral fertilizer has mixed effects. The energy input per hectare is reduced, however so is the crop yield. As a result, the relative net energy input per ton harvest increases (Woods et al., 2010). Reducing yield also implies a need to move production elsewhere in order to maintain the overall supply. This could be in areas that are less suitable and/or lead to land-use change (Ewert et al., 2005). Both are highly relevant reasons for further greenhouse gas emissions (Searchinger et al., 2008; Evans et al., 2009).

Adequate nutrient supply is required to achieve high yields, but negative effects from improper fertilizer use threaten the environmental quality and human health at both local and global scales as a result of water pollution from nitrate leaching or runoff, air pollution and greenhouse gas emission (Cassman et al., 2003). Therefore, it is important to fit fertilization as good to the given situations as possible to improve both, the crop yield and the losses.

One solution for extending the sustainability in agriculture is the implementation of innovations (Rennings, 2000), which not only aims to improve the economic value, but also the ecological value of a product or service. Therefore, the term environmental innovation (or eco-innovation) was introduced by several publications and defined it very broadly as follows (Klemmer et al., 1999; Rennings, 2000; Rennings and Zwick, 2002): Eco-innovations consist of new or modified processes, techniques, practices, systems and products to avoid or reduce environmental harms. According to the concept of sustainable development, the scope of an eco-innovation is to eliminate a harmful environmental impact or if it is impossible to significantly reduce it (Rehfeld et al., 2007; Frondel et al., 2008). While defining eco-innovations they can be divided into three types according to OECD recommendations. The first type of eco-innovations aim to reduces the negative environmental impact of enterprises, which may be achieved by a decreased resource and energy consumption. The second type of eco-innovations is related to recognition and monitoring of environmental problems. The third type means introduction of products and services with reduced environmental impact (OECD, 2005). Eco-innovations may also be referred to as the key element of ‘green’ knowledge-based economy. It contributes to increase in efficiency of the economy due to reduction in material and energy consumption per production unit by using solutions developed in a process that requires intellectual input. Due to the implementation of eco-innovations, the material input used in the process is replaced by knowledge. Eco-innovations should result in limiting the externalities (external costs) and negative environmental impacts, which affects human health and quality of life (Kanerva et al., 2009). Areas for the creation of eco-innovations are: reduction in environmental pressure, environmental benefit compared to an alternative solution, benefit for the entrepreneur, reference to the product/service life cycle, positive effect on the environment regardless of the aim of innovation, systemic change or consumer benefits (Frondel et al., 2008). However, because of their holistic nature, they have more problems in diffusion than other innovations. Therefore, the innovation adoption theories regulated by the technology push or market pull factors needs to be extended (Frondel et al., 2008; Horbach, 2008; Horbach et al., 2012). Overall, the German eco-innovation index, measuring the investment in ecological R&D, companies investment in ecological production and resource effective outcomes, is quite well compared to the rest of the European Union (Eco-innovation index, 2016). However, the agricultural sector still has extensive development potential (Schiefer et al., 2009).

In this thesis in particular and in agriculture in general the focus lays on technical eco-innovations. More popular examples of eco-innovations in agriculture are: Precision agriculture, genetic modified plants or stabilized nutrients in mineral fertilizers.

1.3 Theoretical perspectives

Different theoretical perspectives are used to cover the complexity of fertilizer related environmental impacts and possibilities for improvements. Section 1.3.1-1.3.4 will introduce the different theoretical aspects considered in the present thesis to outline the research on the environmental impact of fertilization and possible drivers for the adoption of eco-innovations. A life cycle assessment analyzed the present impact of modern fertilization (section 1.3.1; Chapter 2). A carbon footprint calculation evaluated the impact of different nitrogen fertilizers on the emission of greenhouse gases (section 1.3.2; Chapter 3). The main drivers and barriers of innovations adoption and diffusion in the fertilizer domain, regarding the type of innovations, were used to analyze the innovation ability in the fertilizer related supply chain (section 1.3.3.; Chapters 4). The investigation of the adoption and diffusion of new technologies (evaluated in eco-innovations) and their usefulness within the German fertilizer supply chain are used in the next section (section 1.3.4; Chapter 5; **Figure 1-2**).

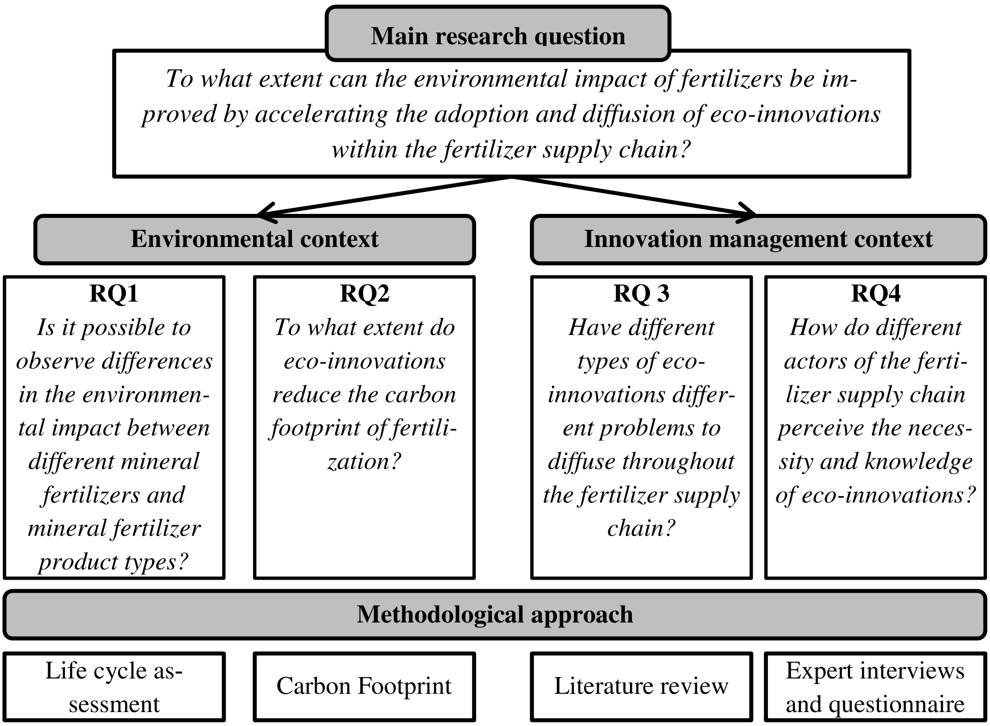

Figure 1-2 Overview of the research questions and methodological approaches.

1.3.1 Life cycle assessment

Life cycle assessment (LCA, also known as life cycle analysis, eco balance or cradle-to-grave analysis) is a holistic consideration of all inputs and outputs of material flows in all stages of the production of a good or service. Additionally a LCA assesses to what extent these material flows affect the environmental impact of a good or service (Brentrup et al., 2004a). This method, certified with two ISO norms (ISO International Standard, 2006a; ISO International Standard, 2006b), is as an instrument for calculation of emissions and harmful effects of products, worldwide accepted and frequently used (Guinee, 2002; Baumann and Tillman, 2004). LCA is a holistic instrument, because it not only evaluates CO_2 emission, but also aspects like land use changes, resource uses, eco toxicities and all kinds of different emissions.

According to ISO (ISO International Standard, 2006a; ISO International Standard, 2006b) LCA is divided into four steps: (1) Goal and scope definition, (2) life cycle inventory assessment, (3) impact assessment and (4) interpretation. The first step in a LCA is always the definition of the goal and scope of the study or research. This step defines the motivation for the LCA study and the intended use of the results. Furthermore this step describes the system under investigation, its function and boundaries. For the LCA of different fertilizer product types, later described in this thesis, this means we investigated the environmental impact of the use of different mineral fertilizers. Subsequently a functional unit (ISO International Standard, 2006a; ISO International Standard, 2006b) is defined, to which all environmental impacts are related to and which should represent the function of the analyzed system.

The life cycle inventory assessment summarizes all resources that are needed (inputs) and all emissions that are released (outputs) by the system under investigation and refers them to the defined functional unit (ISO International Standard, 2006a, ISO International Standard, 2006b). In this preliminary stage primal environmental assessments of a product or service are possible.

The impact assessment aims at a further interpretation of the life cycle inventory assessment data. The inventory data are multiplied by characterization factors to give indicators for the so-called environmental impact categories (ISO International Standard, 2006b):

$$impact\ category\ indicator_i = \sum_j \left(E_j \text{ or } R_j \text{ x } CF_{i,j}\right)$$

with *impact category indicator*$_i$ = indicator value per functional unit for impact category *i*; E_j or R_j = release of emission *j* or consumption of resource *j* per functional unit and $CFi_{,j}$ = characterization factor for emission *j* or resource *j* contributing to impact category *i*.

The characterization factors represent the potential of a single emission or resource consumption to contribute to the respective impact category (ISO International Standard 2006a, ISO International Standard 2006b). An example for such an indicator is the global warming potential (GWP) expressed in CO_2-equivalents, which is derived from the rate of CO_2, CH_4, N_2O and CFC (chlorofluorocarbons) emissions multiplied by their respective characterization factor (e.g. 1 for CO_2, 298for N_2O). According to Goedkoop et al. (2009) and Guinée et al. (2002) the aggregation of inventory results to impact categories is mandatory in life cycle inventory assessment. The list of impact category indicator values for a system under investigation is called its environmental profile.

Table 1-1 List of environmental effects (impact categories) and their characterization factors treated in LCA (modified after Guinée et al., 2002).

	Impact category (Unit)	Unit (impact category)	Impact potential	Unit (impact potential)
Input related	agricultural land occupation	m^2 yr^{-1} agricultural land	agricultural land occupation potential	m^2 yr^{-1} agricultural land
	urban land occupation	m^2 yr^{-1} urban land	urban land occupation potential	m^2 yr^{-1} urban land
	natural land transformation	m^2 natural land	natural land transformation potential	m^2 natural land
	fossil fuel depletion	MJ	fossil depletion potential	kg oil
	mineral resource depletion	kg	mineral depletion potential	kg Fe
	water depletion	m^3 water	water depletion potential	m^3 water
Output related	ozone depletion	ppt yr^{-1}	ozone depletion potential	CFC-11* to air
	climate change	W $(yr/m^2)^{-1}$	global warming potential	CO_2 to air
	terrestrial acidification	m^2 yr^{-1}	terrestrial acidification potential	kg SO_2 to air
	freshwater eutrophication	yr $(kg/m^3)^{-1}$	freshwater eutrophication potential	kg P to freshwater
	marine eutrophication	yr $(kg/m^3)^{-1}$	marine eutrophication potential	kg N to marine water
	human toxicity	-	human toxicity potential	kg 14DCB to urban air
	photochemical oxidant formation	kg	photochemical oxidant formation potential	kg NMVOC+ to air
	particulate matter formation	kg	particulate matter formation potential	kg PM_{10} to air
	terrestrial ecotoxicity	m^2 yr^{-1}	terrestrial ecotoxicity potential	kg 14DCB# to industrial soil
	freshwater ecotoxicity	m^2 yr^{-1}	freshwater ecotoxicity potential	kg 14DCB# to freshwater
	marine ecotoxicity	m^2 yr^{-1}	marine ecotoxicity potential	kg 14-DCB# to marine water
	ionising radiation	man Sv^{-1}	ionising radiation potential	kg U^{235} to air

*CFC-11: Chlorofluorocarbon

+NMVOC: Non Methane Volatile Organic Carbon compound

#14-DCB: 1,4 dichlorobenzene

Table 1-1 gives a list of the impact categories as proposed by Guinee (2002) and Goedkoop et al. (2009). In **Table 1-1** to can be observe that there is a discrepancy in the units. According to

Table 1-1, the indicator for climate change has the unit W $(yr/m^2)^{-1}$. For the characterization factor, one could expect to find the unit W $(yr/m^2)^{-1}$/kg, at least when the emission of greenhouse gases is expressed in kilograms. In the definition of the global warming potentials, however, a reference substance has been introduced, CO_2 to air, so that the characterization factor is a dimensionless number that expresses the strength of a kilogram of a greenhouse gas relative to that of a kilogram CO_2 to air (Guinée et al., 2002).

In the last couple of years many enterprises in agricultural and food production recognized the advantage of environmental calculations and use LCA calculations for marketing reasons (e.g. Arla [Arla foods, 2016], Kraft-Foods [Kraft foods company, 2016], Unilever [Unilever, 2016] or Yara [Yara, 2016]). The primary goal of these efforts is not only to watch on greenhouse gas emissions but also on the total environmental damage and benefit of a product with the aim to create a better production system.

LCA is also a very common and well defined method in estimating the environmental impact of agricultural production and cultivation methods. However, because of its complexity, it is not always easy to categorize and access the quality of the calculation precision and the input data. Many agricultural LCA studies showed that fertilizers have a major impact on the results, nevertheless, they are not very comparable using different approaches and target units (e.g. 1 kg of product or the yield of one hectare) into account (Brentrup et al., 2004a; Brentrup et al., 2004b; Hayashi et al., 2006; Cordella et al., 2008). Obviously it seems necessary to perform a LCA calculation covering the fertilizer itself and not the whole agricultural system. Skowrońska and Filipek (2014) performed a literature review on LCA calculations in the fertilizer area. However, they compared the production, packing, and delivering of the main types of fertilizers, but leaving out the most important part of application and post application emissions. The calculation performed in Chapter 2 tries to close this gap between agricultural LCA studies and consideration of the environmental impacts of the fertilization itself.

1.3.2 Carbon footprint

For the term carbon footprint a unique definition, is unavailable. One of the oldest definitions can be traced back to the term *"ecological footprint"* proposed by Wackernagel and Rees (1998). Wiedmann and Minx (2008) where the first who sharpened the term carbon footprint using the following characterization: *"The carbon footprint is a measure of the exclusive 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."* However, this approach only focuses on CO_2 excluding other greenhouse gases like CH_4 or N_2O. Newer studies and methods on carbon footprint calculations, suggested to include other greenhouse gases as well (Johnson, 2008; Finkbeiner, 2009; Hertwich and Peters, 2009; Minx et al., 2009; Pandey et al., 2011). This is particullar relevant, because the global warming potential of Methan (CH_4) has, in a 100-year timeframe, a 25 times higher global warming potential than CO_2, N_2O even a 298 times higher global warming potential (IPCC, 2007). Moreover not only the greenhouse gases can be counted differently by different studies but also the units of the carbon footprint. The units range from being just a simply indicator expressing the amount of CO_2-emissions (in tons) to indicating an impact quantified in CO_2-equivalents (in tons CO_2-eq) to an area-based unit which presents the needed for compensainge the CO_2-emission in m^2 or km^2 (Wiedmann and Minx, 2008).

Furthermore, there is a lack of uniformity over the selection of direct and indirect emissions. For many studies it is not clear whether the carbon footprint calculation actually include the complete life cycle. For example in a typical flight calculator it is very unspecific, if the tons of CO_2-equivalents include the production of the airplane or other capital goods (Weidema et al., 2008). However, compared to a full LCA addressing all relevant environmental impacts from the product, they are less demanding to perform, and with the strong emphasis on climate change, they have become popular among industries and authorities over the past years (Weidema et al., 2008). The term carbon footprint is present in media, political and environmental discussions. However, the term is still not very uniformity used and even policymakers are not always aware of the dimension of the term carbon footprint. Recently a new ISO Norm (ISO International Standard, 2013) for the carbon footprint methodology is under development.

In this thesis the definition of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Bundesumweltminestrium), the German Environment Agency (Bundes-Umweltamt) and the Institute for Applied Ecology (Öko-Institut) was used which based on the life cycle assessment norm (ISO 14040/44) and includes (Öko-Institut e.V., 2009): The whole lifecycle beginning with the production, extraction and transportation of the ressources and precousers to the production and distibution of the target products followed by the use and subsequent use of the products ending with the disosal and recycling. It includes all greenhouse gas emissions of CO_2, CH_4 and N_2O. A detailed discribtion can be found in Chapter 3. The aim of the carbon footprint calculation in Chapert 3 were to estimate if mineral fertilizera are worse in relation to greenhouse gas emissions than relevant alternatives. Additionally the chapter tries to give an overwive over better possibilities to adopt the fertilization to the specific situation.

1.3.3 The technology acceptance model and its extensions

There are numerous models to describe technology acceptance and use, for example Rogers's theory of innovation diffusion (Rogers, 2003), the Concerns-Based Adoption Model (CBAM; Fuller 1969; Hall 1979) or the technology acceptance model (TAM; Davis 1989). Because of its simplicity and frequent use, the TAM was used as model for innovation adoption in the context of this thesis (**Figure 1-3**). It explains potential user´s behavioral intention to use a technology innovation.

The TAM bases on studies and models of the empirical social science, especially the model of theory of reasoned action developed by Ajzen and Fishbein (1977). Davis (1989) and Davis et al. (1989) thereof developed the TAM to provide an explanation that intended the acceptance of computer usage across a wide range of end-user. According to Straub (2009) Davis identified two perceived characteristics about new technologies which, in his belief, could predict the actual use. Those are the perceived ease of use (EOU) and the perceived usefulness (U). EOU is *the "degree to which a person believes that using a particular system would be free of ef-*

fort" (Davis 1989). U is defined as *"the degree to which a person believes that using a particular system would enhance his or her job performance"* (Davis 1989). A Combination of U and EOU leads to the attitude towards using (A). So U and EUO are the main factor in describing technologies acceptance. Furthermore, U has been found to be a consistent influence of future individual use of technologies (Adams et al., 1992; Agarwal and Prasad, 1998; Lippert and Forman, 2005). Davis (1989) defined usefulness as probability that using a specific application system will increase the job performance of a person. In other words, a person who perceives, that new technologies are useful, has a higher likelihood to adopt a new technology.

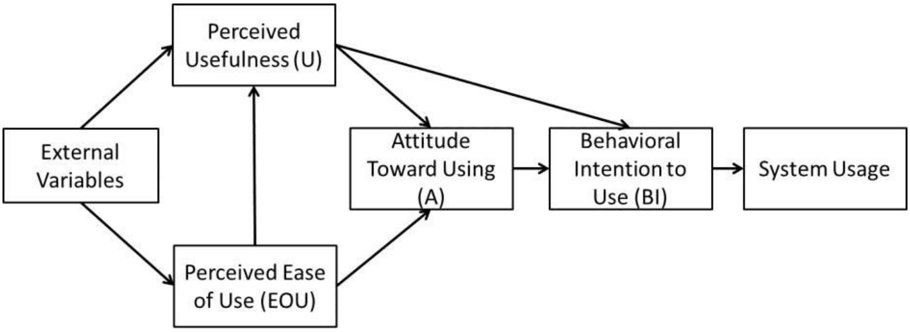

Figure 1-3 Technology acceptance model according to Davis (1989).

However, because of its simplicity and attitude behavior gap, the TAM often fails to actually describe the way of innovation acceptance in agriculture (Flett et al., 2004; Vermeir and Verbeke, 2006; Rezaei-Moghaddam and Salehi, 2010). King and He (2006) found in a meta-analysis several variables, which can improve the forecasting quality of the TAM without changing the simple characteristic of it. The inclusion of external precursors (Jackson et al., 1997; Venkatesh et al., 2000; Negro et al., 2007; Tey and Brindal, 2012), the incorporation of factors suggested by other theories, the inclusion of contextual factors (Straub et al., 1997; Venkatesh et al., 2000; Diederen et al., 2003) and the inclusion of consequence measures (Davis, 1989; Szajna, 1996; Davis and Venkatesh, 2004) are found to be most useful to describe the innovation adoption in a larger scale. For the agriculture sector, the inclusion of consequence measures (such as attitude, perceptual usage and actual usage) is less scientifically investigated and was therefore excluded in Chapter 4 of this thesis.

1.3.4 Diffusion of eco-innovations

Eco-innovations have several difficulties in their diffusion. Here the classic factors pushing innovations in general are mostly not sufficient for the diffusion of eco-innovations. It had been discussed if eco-innovations are driven by technological development (technology push) or by demand factors (market pull). Empirical evidence showed that both are relevant (Pavitt, 1984). In general, new environmental efficient technologies can be summarized under technology push factors, while preferences for environmentally friendly products can be aggregated under market pull factors. Due to the externality problem of eco-innovations, the traditional discussion of innovation economists has to be extended to the influence of the regulatory framework. As shown by Green et al. (1994), Porter and Van der Linde (1995), Kemp et al.

(1998) and Rennings (200) the regulatory framework and especially environmental policy have a strong impact on eco-innovations. Normally they are not self-enforcing and factors like technology push and market pull alone do not seem to be strong enough to encourage the use and adoption of eco-innovations (Rennings, 2000; Horbach et al., 2012).

Concluding on the basic assumptions a simple framework for separating three groups of determinants (technology push, market pull and regulatory push) have been found to be most suitable for describing the development and adoption of eco-innovation (Frondel et al., 2008; Horbach et al., 2012).

Previous studies have shown that the quality and the knowledge base and the level of technological capabilities acquired through R&D activities are found to be very important for the production and diffusion of eco-innovations (Jacobsson and Johnson, 2000; Popp et al., 2011; Costantini et al., 2015). Additionally it is necessary to create a favorable environment for investments. The extent of market demand and the level of prices have been considered encouragements for eco-innovations (Johnstone et al., 2012; Costantini et al., 2015).

Market pull factors may also contribute as determinants of eco-innovations by introducing the concept of customer benefits (Kammerer, 2009). However, studies point out that there are no strong impulses for eco-innovation creation from the demand side since eco-friendly products are still too expensive (Rehfeld et al., 2007). While it is argued that consumers can also drive innovations (Van den Bergh, 2008; Brohmann et al., 2009), only Kammerer (2009) found empirical notably evidence that customer benefits play a key role in eco-innovations as soon as a product delivers an added value to the customer (e.g. organic baby clothes or premium organic food). Wider examples for costumer benefits in the agricultural sector can be: personal health, environmental concerns, animal welfare and the protection of small farms and rural communities (Schleenbecker and Hamm, 2013).

Regulation has been identified as an important determinant of eco-innovation in several empirical studies (e.g. early studies from Green et al., 1994; Cleff and Rennings, 1999; Rennings and Zwick, 2002 or Brunnermeier and Cohen, 2003) and it is known as the "regulatory push/pull effect" (Rennings, 2000; Horbach et al., 2012). Frondel et al. (2007) and Arimura et al. (2007) exposed that policy stringency is generally an increasingly important driving force for eco-innovation rather than the choice of single policy instruments. Facilities facing very stringent environmental regulation are more likely to conduct environmental R&D. In addition, Frondel et al. (2007) point out that the effects of regulation may differ with regard to different environmental technology fields, whereas end-of-pipe technologies are triggered by regulation in particular, cost savings and environmental management systems seem to be more important for the introduction of cleaner technologies.

Additionally, supply chain factors can also play an important role in the development and application of eco-innovations. On the basis of German panel data, Horbach (2008) showed that the improvement of technological capabilities ("knowledge capital") by R&D triggers eco-innovations. Finally, firm specific factors also influence the innovation decision, such as knowledge transfer mechanisms and involvement in networks (Morgan and Murdoch, 2000; Demirel and Kesidou, 2011; Horbach et al., 2012).

Chapter 4 of this thesis addresses the research gap between the knowledge exchange in the fertilizer supply chain and the different assessment of the technology push, market pull and regulatory push by producers, traders and farmers. This part of the thesis follows an exploratory approach on the area of innovation system thinking and knowledge changing in complex networks.

1.4 Research setting: The German fertilizer supply chain

Agricultural supply chains are characterized by complex networks involving a large variety of differently sized companies producing and processing inputs for agricultural production. They are ranging from the input production, the distribution of these inputs to the agricultural production. The fertilizer supply chain in Germany (as well as other agricultural products) is characterized by either one-tier or two-tier distribution starting at wholesale level which sell to several smaller local agro-traders or bigger farmers. Wholesale traders and traders act as both sellers and buyers of many product categories in the supply chain. Farmers often have only one or two regular suppliers on a regional basis. As a consequence, the chain levels between wholesale, traders and agricultural production and vice versa has a bottleneck character. Due to this bottleneck character, the diffusion of information and innovation could be ineffective or influenceable (see Chapter 4).

Table 1-2 Existing fertilizer production capacity for the three main nutrients (nitrogen, phosphorus and potassium) in Germany in 2014 (IVA, 2016).

Company	Location	Capacity in 1000 tons products
Nitrogen		
ALZCHEM AG	Trostberg	145
BASF SE	Ludwigshafen	975
COMPO Expert GmbH	Krefeld	250
DOMO Caproleuna GmbH	Leuna	300
INEOS Köln GmbH	Köln-Worringen	35
SKW Stickstoffwerke Piesteritz	Wittenberg	600
Yara Brunsbüttel GmbH	Brunsbüttel	620
Yara GmbH & CO. KG	Rostock	1500
Total		**4425**
Phosphorus		
ICL Fertilizers Deutschland GmbH	Ludwigshafen	275
Total		**275**
Potassium		
K+S Kali GmbH	Various	7000
Deusa International GmbH	Bleichenrode	90
Total		**7090**

Due to high market entry barriers such as capital and energy costs, expense and environmental standards, only ten fertilizer producers are still operating in Germany (November 2016, **Table 1-2**). However, the producer Compo is more focused on specialty fertilizers for professional application and products for home and garden (like potting soils, plant care or plant protecting products). The nine remaining producers produce more or less exclusively for agriculture and horticulture.

At the trader level, 18 wholesalers were operating in Germany (2013) of which 6 are called Hauptgenossenschaften (cooperative society) and the others are private retailers. Here a strong tendency for further structural change can be expected. The second level of the fertilizer supply chain mainly consists of smaller agro traders. In the year 2013 there were approximately 4000 agro-traders operating as single trading companies or in larger cooperatives in some extent as local distribute channels of wholesalers. However, in the last couple of years this number is constantly decreasing and bigger wholesaler take over the free capabilities. At present about 287500 farmers are operating in Germany (Statistisches Bundesamt, 2013). Including preceding and subsequent areas nearly 10% of the German labor forces, approximate 4.0 million people, are working in or with the agricultural sector.

In the business year 2015/16 a total amount of 1,7 Mt of nitrogen, 0,3 Mt of phosphorus and 0,4 Mt of potassium were delivered to German farmers (Statistisches Bundesamt, 2015). That means in theory, that all nutrients except phosphorus could be covered with the inland production (compare **Table 1-2**). However, 66% of the nitrogen and 94% of the phosphorus used in German agriculture originated from other European (EU-15) or eastern European countries (IVA, 2016). One explanation could be the price sensitivity of farmers for the acquisition of fertilizers. Farmers are only paying a small amount (5-10%) of the operating costs for fertilizers. However, in the last couple of years the volatility and unpredictable changes in pricing and availability changed significantly. Especially the purchase of fertilizer will be restricted with price peaks and postponed to other years (Huang, 2009). Additionally, the fertilizer production in Germany is, due to the personal and raw material costs and environmental standards, more expensive than in other countries. With a trading volume of 1.9 billion € for the three main nutrient in 2014 the fertilizer costs for German farmers should not be underestimated (**Table 1-3**).

Table 1-3 Average costs and expense value for the three main nutrients in Germany in 2014 (IVA, 2016).

Nutrient	Average price per ton in €	Expense in million € (without value added tax)
Nitrogen	842	1440
Phosphorus	875	251
Potassium	674	268

1.5 Aims and outlines of the thesis

Fertilizers have relevant effects on the agricultural sustainability (see Chapter 1.2). In this thesis, the objective was to give a broader view on how different production types and fertilizer raw materials could enhance the agricultural sustainability without discredit any type of farming (conventionally or organic). The Chapters 2 and 3 focuses more on an agricultural perspective, the following Chapters 4 and 5 expose an inside view into the fertilizer supply chain and the innovation system.

Table 1-4 Overview of the study design.

	Chapter	Level of consideration	Theoretical perspective	Measured variable	Measurement	Theoretical approach
Assessment of the environmental impact	2	Environmental impact of the fertilizer life cycle	Life cycle perspective	Mineral fertilizers	Library of life cycle data Expert interviews (n=8) Scientific publications	Life cycle assessment
	3	Greenhous gas emission arising by the use of fertilizers	Live cycle perspective	Nitrogen fertilizers	Library of life cycle data Expert interviews (n=8) Scientific publications	Carbon footprint
Eco-innovations management perspective	4	Problems of eco-innovation diffusion in the area of plant nutrient and fertilization	Supply chain perspective	Fertilizer supply chain and Famers	Scientific publications	Extended technology acceptance model, different types of innovations
	5	Knowledge and adoption of eco-innovation in the German fertilizer supply chain	Supply chain perspective	Fertilizer supply chain	Questionnaire (n=57) Expert interviews (n=8)	Theories of innovation adoption, knowledge sharing, eco-innovations

Chapter 2 will give an overview of existing mineral fertilization practices and their environmental impact. In the course of stricter limitation values for the use of nitrogen and phosphorus in Europe coming along with the agenda 2020 (Nachhaltigkeitsstrategien für Deutschland, 2016), a more environmental friendly application and use of fertilizers is necessary. A number of studies investigated the environmental impact of nitrogen fertilizers (Brentrup et al., 2000; Brentrup et al., 2004b; Ahlgren et al., 2010; Nemecek et al., 2011b). However, other important plant nutrients or the fertilizer product types were not taken into account. A comparison of different mineral fertilizer types and production types will give an answer to the question of how major the environmental impact of mineral fertilizers currently is (where we stand). This can be specified with the following two research questions focusing on the existing environmental impact of fertilizers:

Research question 1: *Is it possible to observe differences in the environmental impact between different mineral fertilizers (1.1) and mineral fertilizer product types (1.2)?*

To evaluate these differences, a holistic life cycle approach was used concerning the fertilizer-specific categories climate change, fossil fuel depletion, acidification, eutrophication and resource depletion. Data were gathered from Davis and Haglund (1999), Jenssen and Kongshaug (2003), Wood and Crowie (2004), and IPCC (2007). These data combined with the database ProBas (Umweltbundesamt and Öko-Institut, 2016) and expert interviews with members of every step in the fertilizer supply chain in Germany, provided detailed information about the emission of transport systems and the fertilizer logistics.

Chapter 3 seeks to consider the emissions of greenhouse gases related to the (mineral) fertilizer application (where we could go). Numerous eco-innovations in the field of fertilizer types and fertilizer application techniques have been generated in the last decades (Renni and Heffer, 2010). Yet their carbon footprint has not been compared. Therefore, the following research question was framed:

Research question 2: *To what extent do eco-innovations reduce the carbon footprint of fertilization?*

The carbon footprint was used as tool to estimate if existing alternatives of mineral fertilizers decrease the environmental impact of the fertilization itself. The emission of greenhouse gases was used for the comparison, because many agricultural LCA studies claimed that fertilizer are responsible for a high contribution to greenhouse gas emissions (e.g. Brentrup et al., 2004a, b; Cordella et al., 2008; Hillier et al., 2009; Khoshnevisan et al., 2013; Nemecek et al., 2011a, b). All fertilizer alternatives (stabilized nitrogen fertilizer and secondary raw material fertilizers) were selected because they all have as main goal to reduce these emissions without compromising on crop productivity. Additionally, the effect of the combination of irrigation with fertilization (i.e. fertigation) was investigated.

Chapter 4 summarizes theories of innovation adoption and extends these theories by regarding the characteristics of innovation itself and their adoption and diffusion in agricultural supply chains in general and the fertilizer supply chain in particular. Numerous eco-innovations have been developed in the last decades. However, none of them has gained a major market share in Germany or other developed countries. To evaluate whether this non-adoption stems from the fact that these alternatives are not as environmentally friendly as promoted or are due to other reasons following research question was framed:

Research question 3: *Have different types of eco-innovations different problems to diffuse throughout the fertilizer supply chain?*

Here a general overview of the existing literature on innovation adoption and diffusion in the plant nutrition area was made which was combined with in-depth exploration of the significant drivers which aims to explain the innovation adoption. Here the TAM (Davis et al., 1989) was used as basic approach and extended by influencing variables from other theories of innovation adoption to get a better understanding of innovation adoption in the fertilizer sector. Secondly the main characteristics, explained in disruptive and continuous innovations, and innovation types were taken into account. It was aimed to obtain a better understanding of the adoption of eco-innovations in general to propagate their diffusion. This leads to second part of this thesis: What do we know about the acceptance of more environmental friendly fertilizer products or application techniques making the whole fertilization more sustainable.

Chapter 5 aims at contributing to our understanding of the dynamics of the need of eco-innovation adoption and knowledge sharing of the German fertilizer supply chain. In the literature, a company´s decision to introduce eco-innovations is influenced by a variety of factors including regulation, technology push, market pull, policy and firm specific aspects (Davis, 1989; Rogers, 2003; Frondel et al., 2008; Horbach, 2008; Horbach et al., 2012; Dolinska and d'Aquino, 2016). Here major theoretical perspectives from the area of innovation creation and adoption are discussed to understand why eco-innovations are not adopted by users. With approaches from information exchange interactions, knowledge sharing through networks, innovation system thinking and basics from the theory of innovation adoption it aims an explanation for the non-adoption of innovation in the German fertilizer supply chain (Tepic et al., 2012; Totin et al., 2012). Additionally, the knowledge of selected existing eco-innovation outlines a better inside view on the information exchange and knowledge sharing within the fertilizer supply chain (what they know). All together Chapter 5 aims to answer the following research question:

Research question 4: *How do different actors of the fertilizer supply chain perceive the necessity and knowledge of eco-innovations?*

To answer these research questions, a two-step approach was conducted to asses these findings. First exploratory expert interviews with eight actors of the fertilizer supply chain concerning environmental, economic and technological changes were conducted. Secondly, the statements generated thereby were fed into a semi-structured questionnaire answered by 57 participants stemming from fertilizer production (n=12), traders (n=34) and farmers (n=11) level.

Finally, Chapter 6 concludes the thesis and reflects on the key findings and answers the main research question. Additionally, Chapter 6 provides the theoretical contribution of the thesis, the recommendations to future research, policy and management implications. The structure of the thesis is visualized in **Figure 1-4**.

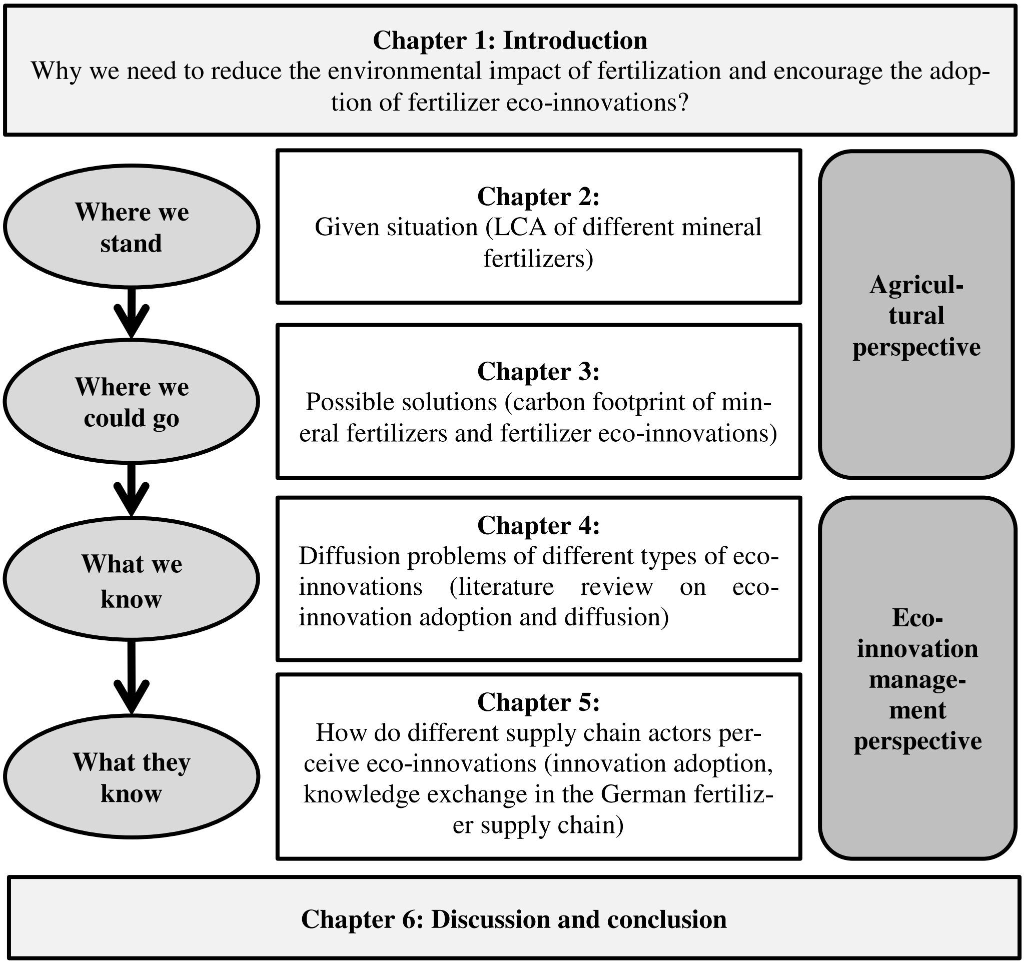

Figure 1-4 Thesis setup.

2. Where we stand: Evaluating the environmental impact of different fertilizer product types by using life cycle assessment

Chapter 2 answers research questions 1.1 and 1.2:

Is it possible to observe differences in the environmental impact between different mineral fertilizers (1.1) and mineral fertilizer product types (1.2)?

2.1 Introduction

With the growing world population and the rising demand for renewable energy sources and raw materials it is even more important to grow plants with efficient usage of nutrients (Challinor et al., 2009; Spiertz and Ewert, 2009; Spiertz, 2010). However, because of more intense crop production during the last decades the environmental impact on non-agricultural ecosystems has already increased significantly. For a sustainable crop production the replacement of nutrients exported from the soil via the harvest is essential. In conventional farming this can be partly done by recycling of nutrients with organic manures (e.g. farm yard manure, slurry, compost). However, application of mineral fertilizers is the most important way of filling up the soil nutrient pool. The production and application of nitrogen (N) fertilizers causes a lot of greenhouse gases emissions (especially nitrous oxide [N_2O]) and is based on high energy consumption (Davis and Haglund, 1999; Bellarby et al., 2008; Brentrup and Pallière, 2008). In

This chapter is based on the following publication: Hasler, K., Bröring, S., Omta, S. W. F. & Olfs, H.-W. (2015). Life cycle assessment (LCA) of different fertilizer product types. *European Journal of Agronomy,* 69, 41–51.

most regions of the world N is the most important mineral nutrient for cereal production, and an adequate supply is essential for high yields and quality (Mulvaney et al., 2009). Additionally, the principles of sustainability have found their way to policy and consumer decisions (Burton, 1987; Tilman et al., 2002). In the near future, this might lead to a new direction in food production. Not only the price and quality of a product are increasingly important for actors in the food supply chain, but society will increasingly focus on the sustainability of the entire production process. Hence, in the future farmers and food producers will be encouraged to adopt environmental-friendly solutions to meet the requirements of certification and labeling along the entire value chain (e.g. carbon footprints; Bellaraby et al., 2008; Spiertz, 2010).

In crop production different fertilizer product types (FPT) can be distinguished: fertilizers with only one nutrient (single nutrient fertilizer, SN) or with more than one nutrient (compound fertilizer). Compound fertilizers can further be divided in complex fertilizers (CF) and so-called “bulk blends” (BB). The difference between these two is that complex fertilizers are produced by a chemical process within a factory using different nutrient sources while BBs are dry mixtures between several SN fertilizers. As a result, complex fertilizers contain ideally the same nutrient composition in every fertilizer grain.

To evaluate the environmental impact of different FPTs a life cycle assessment (LCA) is an appropriate tool, because it takes all relevant impacts occurring during the entire life cycle into account (Guinee, 2002; Baumann and Tillman, 2004). It allows quantifying and estimating the environmental impact of products or services and in addition it is a possibility to assess environmental improvements. Especially food and agricultural products are often investigated via LCA (e.g. Cellura et al., 2012; Milà i Canals et al., 2006; Torrellas et al., 2012). In many studies (e.g. Brentrup et al., 2004a, b; Cordella et al., 2008; Hillier et al., 2009; Khoshnevisan et al., 2013; Nemecek et al., 2011a, b) it was shown that fertilization is responsible for a high amount of emissions, especially of greenhouse gases. In most of these studies, fertilizer production and the emission of N_2O after fertilizer application show major impacts on the LCA results (see Brentrup et al., 2004a, b; Torrellas et al., 2012). Agriculture is accused of producing 10 to 12 % of all greenhouses gases worldwide with approximately 38 % of these emissions coming from organic or mineral fertilizers (IPCC, 2007; Smith et al., 2007). Adopting the fertilizer input to the environmental preferable system can lower agricultural emissions and improve the overall environmental impact of agriculture. In several studies mineral fertilizers have been compared with organic fertilizers (Brentrup et al., 2004b; Martínez-Blanco et al., 2011; Spangberg et al., 2011), but mostly only information on the amount of applied fertilizers is provided and not the exact nutrient form. So far to our best knowledge different product types of mineral fertilizer have not been studied.

Moreover, in the existing studies rather heterogeneous results are presented, mostly because as so-called “functional unit” either the weight of the produced goods or the area used for crop production has been used (Brentrup et al., 2004a; Hayashi, 2012). Some studies come to the conclusion that rather extensive than intensive crop production can be claimed as more sustainable (e.g. Hayashi et al., 2006). Other studies state that even intensive cultivation can be more sustainable, because for higher yields less land is occupied (Brentrup et al., 2004b; Nemecek et al., 2006). Therefore, further research on the role of fertilizers in the LCA of food production seems necessary.

Apart from the reliability of agricultural LCA studies, the fertilizer market is constantly changing with agricultural policy decisions (for example EG regulation No 73/2009) and market prices. In Germany market shares of complex fertilizers shifting downwards (Statistisches Bundesamt, 2013) and with a market share of less than 15% they become more and more a niche product for horticulture and special crops (Fertilizer Europe, 2013; Statistisches Bundesamt, 2013). That is why horticultural LCA studies are mostly based on complex fertilizers (e.g. Blengini and Busto, 2009; Cellura et al., 2012; Martinez-Blanco et al., 2011). In this context Neto et al. (2013) mentioned that the carbon footprint of wine varies in a wide range (from 0.33 to 2.5 kg CO_2 eq./0.75 L) because of the different amounts and compositions of the fertilizer used and emphasized that further investigations are necessary to understand these differences.

The aim of our study was to assess the environmental impact of different FPTs. Based on the hypothesis that diverse product types used in agriculture practice result in differing environmental impacts it is intended to convince partners in the fertilizer supply chain (e.g. agro dealers, farmers) that emission mitigation in agricultural systems is achievable by choosing the most favorable FPT. Another reason for our investigation was to analyze the environmental impact of different fertilizer products along the supply chain. The analysis was performed on three kinds of different FPTs (CF, SN and BB). Additionally we evaluated different components of BB fertilizers and the equivalent SN fertilizers. Especially nitrogen fertilizers are produced in different forms (e.g. nitrate, ammonium and/or urea based) and have different emissions during production and application (EFMA 2000a-g). Calculations take into account the use of different basic materials, such as diammonium phosphate (DAP), triple superphosphate (TSP), calcium ammonium nitrate (CAN) or urea, enabling a comparison between these alternatives in order to verify the environmental preferable one. Many studies revealed that N_2O emissions during fertilizer production are responsible for the overall high environmental impact of fertilizer usage (Brentrup et al., 2000; Ahlgren et al., 2008; Martinez-Blanco et al., 2011). To assess the relevance of this important factor, a scenario analysis with lower N_2O emissions during nitrogen fertilizer production was performed.

2.2 Methods

2.2.1 Investigated system

From the 109 million tons N fertilizer used worldwide, about 60% is urea (FAO, 2012; Glibert et al., 2006). According to good professional praxis (EFBA, 2007) urea should not be used for bulk blending, since it produces problems of segregation and hydrolysis. However, because of its widespread worldwide distribution as SN fertilizer, urea was taken into consideration in our LCA study. In Europe CAN is the dominating nitrogen fertilizer (Ahlgren et al., 2008;

Fertilizer Europe, 2013). The main phosphorus (P) fertilizer in Europe is DAP (Fertilizer Europe 2013). To evaluate whether the phosphorus form plays an important role for the calculation of the environmental impact of fertilizers, a single nutrient phosphorus fertilizer (TSP) was considered as well. Potassium (K) fertilizers are less critical from an environmental point of view. Therefore only muriate of potassium (MOP), a potassium chloride based product, was taken into account.

To get an idea of the variability of different FPTs and the variation in nutrient application rates detailed facts about the fertilizer supply chain were collected from various actors in the German fertilizer supply chain. To account for the different production context (e.g. fertilizer logistics, soils, livestock intensity, farm sizes) two different regions in Germany were distinguished (North-West and South-West Germany; see **Figure 2-1**).

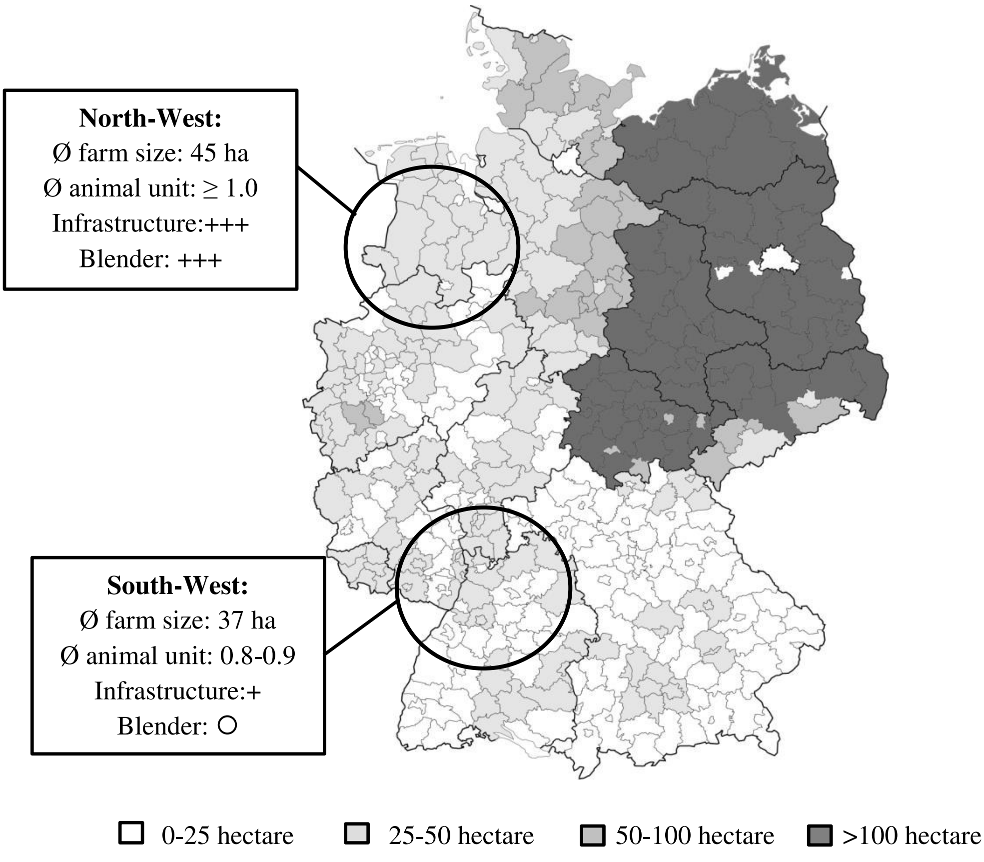

Figure 2-1 Average farm size in Germany at district level and selected regions based on animal density per hectare farmland, transportation infrastructure, number of fertilizer blenders and preferred complex fertilizer.
○ = below average / + = average / ++ = above average

North-West Germany is an agricultural region with extreme high livestock intensity, while small scale farms focusing on horticultural and special crops dominate the South-West. In addition the infrastructure in these two regions is quite different. In North-West Germany all relevant transportation systems for fertilizers (i.e. ship, train and truck) are available and the number of ports and transshipment terminals is high. The South-West region has a long tradition of shipping via the Rhine, but the train infrastructure is rather limited. Based on the agronomic situation within these regions two typical fertilizer nutrient compositions were selected. A NPK fertilizer with a low P content (17-5-13 = 17% nitrogen, 5% phosphorus [as P_2O_5] and 13% potassium [as K_2O]) is often used in areas with high livestock intensity, because manure already contains high amounts of P (North-West), while a NPK with an balanced nutrient composition (15-15-15 = 15% of nitrogen, phosphorus and potassium) is mostly used in regions with arable farming, horticulture or cultivation of special crops (South-West; Statistisches Bundesamt, 2013).

2.2.2 Model assumptions and data sources

According to ISO norms 14040 and 14044 (ISO 2006a, b) an LCA contains four stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the end results. Goal and scope definition are essential to identify the functional unit, the system boundaries, the cut-off criteria and data sources. Life cycle inventory consists of a detailed compilation of all relevant inputs (material and energy) and outputs (gaseous, liquid and solid emissions to air, water or soil) at each stage of the life cycle. LCIA aims to quantify the relative importance of all the environmental burdens identified in the LCI by analyzing their influence on selected environmental effects. Finally, in the interpretation phase, all the results are analyzed in order to derive conclusions and recommendations from the previous calculations.

The scenarios and impact assessments were modeled and computed via the OpenLCA software tool (GreenDelta, Berlin, Germany) by using the ReCiPe midpoint impact assessment method (hierarchist version). The ReCiPe life cycle impact assessment method is based on 18 different categories to evaluate the environmental impact of products or activities (Goedkoop et al., 2009). Eight of these categories (i.e. ozone depletion, photochemical oxidation formation, particle matter formation, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation and urban land occupation) were excluded from this study due to their limited relevance (estimated less than 0.5% of the overall damage) in the fertilizer supply chain (Baumann and Tillman, 2004; Brentrup et al., 2004b; Ahlgren et al., 2008). We also exclude agriculture land occupation and natural land transformation because we assumed that fertilizer application in Germany takes place on areas already used for many years in agricultural production. Furthermore we did not consider marine eutrophication, even though it is one of the most relevant environmental burdens related to fertilization, but within our system boundary it played a very minor role (see **Table 2-3**). Finally, the impact category water depletion has no relevance, because almost all of the process water in fertilizer production is recycled.

For this study the following impact categories were selected: Climate change (expressed in kg CO_2-equivalents), terrestrial acidification (expressed in kg SO_2-equivalents), freshwater eutrophication (expressed in kg N-equivalents), fossil fuel depletion (expressed in kg Oil-equivalents) and resource depletion (expressed in kg Fe-equivalents). These impact categories have been selected on the basis of relevant issues associated along the fertilizer supply chain and according to the differentiation potential between the forms of fertilizers (Brentrup et al., 2004a; Skowrońska and Filipek, 2014).

The impact category climate change (also known as the assessment of greenhouse gas emissions) was chosen because N fertilizer especially contributes to N_2O emissions, a gas with a global warming potential that is 298 times greater than that of CO_2 (IPCC, 2007) based on a hundred years' time period (IPCC, 2001). Emissions of N_2O essentially occur during the production and post-application of fertilizers. Emission of CO_2 is mainly related to the combustion of diesel used for transportation and farm operations. When using urea as N fertilizer it has to be kept in mind that during urea production less CO_2 is emitted (CO_2 reacts with NH_3 to form the urea molecule $CO(NH_2)_2$) compared to other nitrogen containing fertilizers, but the CO_2 emissions after field application are higher (due to CO_2 release after hydrolysis of the urea molecule) as for other nitrogen containing fertilizers (Davis and Haglund, 1999; Brentrup et al., 2000; Brentrup and Pallière, 2008).

Terrestrial acidification allows an assessment of the impact of ammonia (NH_3), sulphur dioxide (SO_2) and nitrogen oxide (NO_x) on the environment (see Roy et al., 2012). It takes into account the increasing concentration of acidifying substances in the lower atmosphere, which finally leads to "acid rain". Depending on the N form (nitrate, ammonia, or urea) the application of fertilizers in the field is followed by variable emissions of NH_3 through volatilization. SO_2 emissions are mainly caused during the production of electricity and combustion of diesel. NO_x is essentially associated with diesel combustion during transportation and fertilizer production.

The eutrophication potential can be used to assess the impact of post application nitrate and phosphorus leaching as well as surface runoff to ground and/or surface waters. Here especially winter is the risky period in terms of leaching (Brentrup et al., 2004b).

Fossil fuel depletion has been selected as relevant impact category for our LCA because the production, especially of nitrogen containing fertilizers, is highly energy intensive. For example, ammonia synthesis, which is the precursor of nearly all mineral nitrogen fertilizers, accounts for approximately 1% of the total global annual energy consumption (Dawson and Hilton, 2011).

Resource depletion was selected because with phosphorus and potassium, two finite mineral resources are used in fertilizer productions which, unlike fossil fuels, have no substitutes(Skowrońska and Filipek, 2014). It was assumed that 2.6 to 3.5 kg phosphate rocks are required to produce one kg of P fertilizer (EFMA, 2000f). Potash salts were assumed to contain 63.2% K_2O (Garret, 1996) which can be used in fertilizer production and that 10.5 kg potash salts are needed to produce one kilogram fertilizer (Umweltbundesamt and Öko-Institut, 2016). Additionally the production of diesel from crude oil requires further limited raw materials. Natural gas is predominantly used for N fertilizer production as process gas and energy source (EFMA 2000a, b, d, e, f, g).

Data for the calculation of the emission inventory data were taken from the ProBas (2012) database. This database includes details on all emissions related to transport services and some concerning fertilizer production. Further data for fertilizer production (with the exception of the potassium data) were extracted from Davis and Haglund (1999). Emissions at field level are determined by establishing nutrient balances and by use of models for the emission of N_2O, NO, NH_3, N_2, NO_3 and CO_2 directly after fertilizer application with the models described in IFA and FAO (2001) and IPCC (2000; 2003; for detailed information see **Table 2-1**).

Table 2-1 Data sources for emissions related to the different systems.

Resources/emissions	Sub-System	Data Source
Fossil Fuels (oil, natural gas, hard coal)	Fertilizer production	Yara (personal communication), K+S (personal communication), Patyk and Reinhardt (1996); Davis and Haglund (1999); Jenssen and Kongshaug (2003); Umweltbundesamt and Öko-Institut (2016)
	Transportation	Umweltbundesamt and Öko-Institut (2016)
	Farm machinery	KTBL (2009)
Minerals (phosphate rock, potash salts)	P and K fertilizer production	Davis and Haglund (1999), Umweltbundesamt and Öko-Institut (2016)
CH_4, CO_2, CO, NO_x, particles, SO_2, NMVOC*, N_2O, NH_3, N-tot, P-tot	Fertilizer production	Davis and Haglund (1999), Yara (personal communication), K+S (personal communication), Umweltbundesamt and Öko-Institut (2016)

*non-methane volatile organic compounds

2.2.3. Functional unit and system boundaries

All environmental impacts were related to the functional unit of 300 kg complex fertilizer with a nutrient composition of 17-5-13 or respectively 15-15-15 applied to 1 hectare arable land. Related to the functional unit used for the LCA calculations (i.e. applying 300 kg product per hectare), a CF with the nutrient composition 17-5-13 and all SN/BB products contain 51 kg nitrogen, 15 kg phosphorus and 39 kg potassium, while the 15-15-15 based products contain 45 kg nitrogen, phosphorus and potassium. Fertilizer dosage was calculated by taking into account the typical crop needs for a first dressing under German spring conditions. The three different combinations (SN/BB) for each NPK formula have the same nutrient composition, but due to different nutrient contents of the basic fertilizers the SN or BB fertilizer systems result in less or more than the 300 kg product of the complex fertilizers (see **Table 2-2**).

Table 2-2 Different combinations of components to get single nutrient and bulk blend fertilizers equivalent to 300 kg complex fertilizer 17-5-13 or 15-15-15 per ha.

Nutrient content	Components	Mass (kg)	Total mass (kg)
17-5-13	CAN* (26,5% N)	175	
	MOP+ (40% K_2O)	97	
	DAP# (18% N, 46% P_2O_5)	26	
			298
	Urea (46% N)	111	
	MOP (40% K_2O)	97	
	TSP° (45% P_2O_5)	27	
			235
	CAN (26,5% N)	192	
	MOP (40% K_2O)	97	
	TSP (45% P_2O_5)	27	
			315
15-15-15	CAN* (26,5% N)	102	
	MOP+ (40% K_2O)	113	
	DAP# (18% N, 46% P_2O_5)	98	
			313
	Urea (46% N)	98	
	MOP (40% K_2O)	113	
	TSP° (45% P_2O_5)	100	
			311
	CAN (26,5% N)	167	
	MOP (40% K_2O)	113	
	TSP (45% P_2O_5)	100	
			380

*Calcium ammonium nitrate
+Muritate of potash
#Diammonium phosphate
°Triple superphosphate

The system boundaries for the LCA calculations were defined as: mining of the raw materials and extraction of the nutrients from these materials, transportation of raw materials and pre-products, manufacturing of the fertilizer products, all transportation processes of the final fertilizers to the different marketplaces (agro dealer and/or wholesalers), application of the fertilizer, the related field operations and emissions directly after fertilizer application in the field (**Figure 2-2**).

Interviews with members of every step in the fertilizer supply chain in Germany provided detailed information about the fertilizer logistics. Based on this knowledge fertilizer supply chain models were developed for the two selected regions with a three stage supply chain approach, leading from producer over wholesaler and agro dealer to farmer which is widely used in German fertilizer trading. An empty return trip for trucks was only assumed at agro dealer and farm level. Emissions from capital goods, buildings as well as from 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).

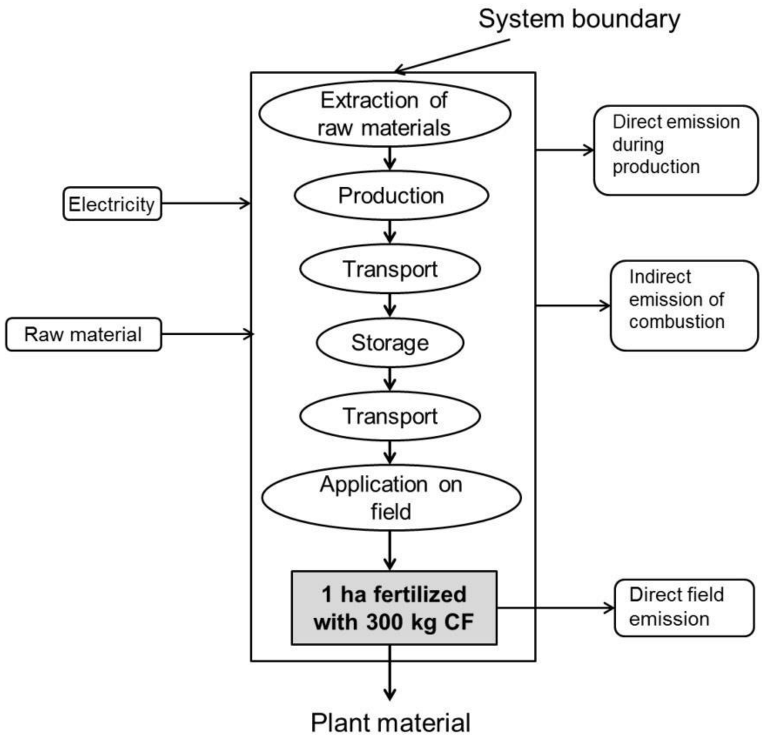

Figure 2-2 System boundaries for the LCA calculations of the fertilizer supply chain in Germany (material inputs during the production process and emissions taken into account; emissions from capital goods, buildings and the production of machinery were not included).

2.2.4. Statistical calculations and scenario analysis

We started the data evaluation with a statistical model with the FPT and region as influence factors. However, because of very limited differences we decided to use the region only as variation for further statistical analysis. All statistical differences were determined by using the Tukey test at a significance level of $p<0.05$. Calculations were carried out using the software R (R Development Core Team, 2015).

A scenario analysis was conducted to assess the influence of changes in important parameters to evaluate the solidity of the end results. The effect of changes in N_2O emissions during fertilizer production was chosen as the most important factor influencing the LCA results of the fertilizer supply chain. This is based on the fact, that N_2O emissions during production has been reduced significantly in European fertilizer plants during the last couple of years (IFA and

ICIS, 2015). For the scenario calculation a reduction of 70% and 90% compared to the current worldwide N_2O emission were compared for both NPK nutrient compositions. This reduction technology is already implemented for western European fertilizer plants.

2.3 Results

2.3.1. Cradle-to-field inventory

The results of the cradle-to-field inventory are divided into resources, emission to air and emission to water. The values shown in **Table 2-3** are the minimum, the average and the maximum emissions. These emissions were selected, because earlier agricultural LCA studies have shown their importance for fertilizer investigations (e.g. Ahlgren et al., 2008; Brentrup et al., 2004a,b).

Table 2-3 Average resources used and emissions to air/water from the cradle-to-field inventory for the application of 300 kg complex fertilizer with a nutrient composition of 17-5-13 (i.e. 17% N, 5% P_2O_5 and 13% K_2O) and 15-15-15 (i.e. 15% N, 15% P_2O_5 and 15% K_2O) or equivalent amounts of nutrients via single nutrient or bulk blend fertilizers (see **Table 2-2**).

		17-5-13			**15-15-15**		
	unit	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**
Resources							
Phosphate rock	kg	15.9	32.0	45.8	59.9	61.2	63.7
Potash salt	kg	72.4	92.2	111.9	83.5	91.6	139.9
Hard coal	MJ	200.9	211.5	238.8	173.8	176.7	180.7
Oil	MJ	272.4	286.6	232.1	237.0	240.4	245.1
Natural gas	MJ	1613.3	1721.6	2004.3	1403.3	1485.7	1671.0
Diesel	MJ	18.7	32.8	42.2	44.2	53.9	65.3
Emission to air							
CO_2	kg	260.2	240.0	299.8	218.5	282.9	312.6
NO_x	kg	2.369	2.692	2.886	1.070	1.172	1.337
N_2O	kg	0.848	1.556	2.001	0.358	0.932	1.557
CO	kg	0.165	0.218	0.250	0.208	0.238	0.268
SO_x	kg	0.463	0.520	0.716	0.937	1.095	1.434
CH_4	kg	0.208	0.234	0.260	0.164	0.251	0.292
NH_3	g	-	19.6	39.1	-	81.7	163.2
Emission to water							
NO_3-N	kg	0.359	0.436	0.482	0.459	0.504	0.581
N to water	g	0.274	3.9	22.7	0.546	4.9	23.7
P to water	mg	0.231	0.955	1.917	0.786	4.3	6.9

2.3.2. Impact assessment

For the LCA calculation only the preferred nutrient composition within each region was taken into account (17-5-13 for North-West and 15-15-15 for South-West). Because of the relatively minor relevance of the transport processes (the transportation system is only responsible for 1 to 3 % of all emissions) we pooled the datasets for both regions in our calculations (see **Figure 2-3**). These regions mainly differ in their infrastructure and the transport distances making it simple to adapt the results from our study using Germany as a test case to other agricultural environments and regions. However, it should be mentioned, that particularly truck transportation over long distances can deteriorate the end results.

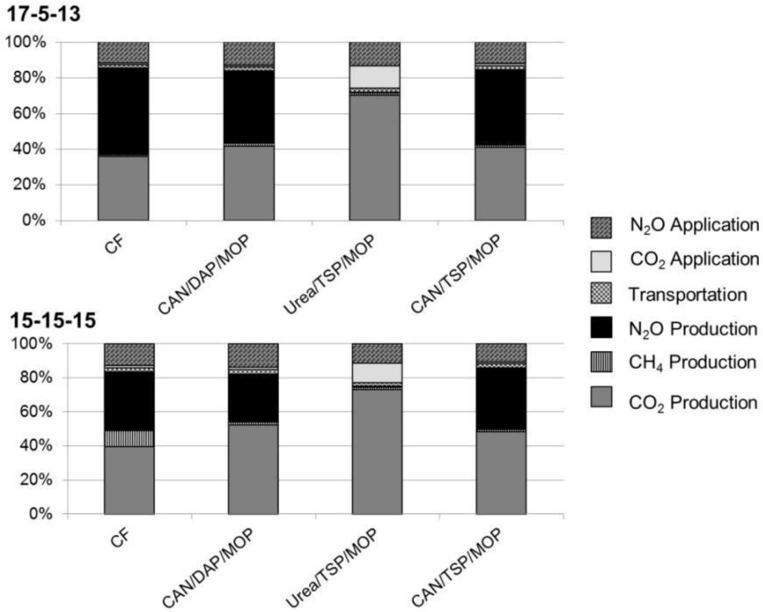

Figure 2-3 Contributions of the main supply chain steps (production, transport and application) to the impact category climate change for a fertilizer with the nutrient composition 17-5-13 and 15-15-15; CF: complex fertilizer; /// all three components are blended and the final blend is applied in one application; CAN: Calcium ammonium nitrate; MOP: Muritate of potash; DAP: Diammonium phosphate; TSP: Triple superphosphate.

Climate change

Especially the emissions of greenhouse gases play an important role in the fertilizer supply chain. The production of mineral fertilizers causes greenhouse gases in a large extent (mainly CO_2) due to the use of fossil fuels in the ammonia production and in a lesser extent due to the reaction of rock phosphate with sulphuric acid or during the extraction of phosphorus or potassium from parent rock materials. Therefore, climate change is the most important category in our investigation.

Applying FPTs with a nutrient composition of 17-5-13 result in emissions of 487 to 560 kg CO_2-equivalentes (**Table 2-4**). The significantly higher emissions for the complex fertilizer indicate that this fertilizer type seems to be less appropriate considering only greenhouse gas emissions. Pairwise comparison of the CO_2-equivalentes for SN and BB for each of the three combinations reveals no significant differences, but the three different composition of the SN and BB fertilizer lead to significantly different emissions of CO_2-equivalents. SN or BB based on urea, MOP and TSP or based on CAN, MOP and DAP seem to be the most sustainable options for a fertilizer with a low phosphorus and high nitrogen and potassium content (488 kg respectively 498 CO_2-equivalentes). The 15-15-15 FPTs show overall lower emissions (391 to 524 kg CO_2-equivalentes; **Table 2-5**). Again the fertilizer with urea, MOP and TSP is the environmentally most beneficial FPT (391 kg CO_2-equivalentes), but even the complex fertilizer (432 kg CO_2-equivalentes) is quite a good option if only the greenhouse gas emissions are taken into account. The CAN, MOP and TSP based products show significantly higher emissions. The right choice of the ingredients in the FPTs can therefore significantly reduce emissions to the air.

Table 2-4 Impact results for each impact category and for the different fertilizer product types for all life cycle stages for applying 300 kg of a 17-5-13 complex fertilizer (i.e. 17% N, 5% P_2O_5 and 13% K_2O). Statistically significant differences within each impact category are expressed in different letters based on a Tukey test ($p \leq 0.05$).

Fertilizer product type	Impact categories							
	Climate change (kg CO_2-eq)		Fossil fuel depletion (kg oil-eq)		Acidification (kg SO_2-eq)		Eutrophication (kg N-eq)	Resource depletion (kg Fe-eq)
Complex	560	d	54.1	c	1.52	bc	1.60	0.016
CAN/MOP/DAP	497	b	52.3	b	1.35	ab	1.37	0.012
CAN+MOP+DAP	500	b	52.3	b	1.55	c	1.36	0.013
Urea/MOP/TSP	487	a	46.7	a	1.20	a	1.17	0.011
Urea+MOP+TSP	489	a	46.7	a	1.41	bc	1.17	0.012
CAN/MOP/TSP	529	c	57.7	d	1.37	ab	1.39	0.013
CAN+MOP+TSP	532	c	57.7	d	1.56	c	1.39	0.013
RSE*	3.1		0.04		0.16		ns+	ns

/// all three components are blended and the final blend is applied in one application

+++ the three components are applied in three application steps

*Residual standard error

+not significant

Compared to the 17-5-13 complex fertilizer the urea and DAP based FPTs show more than 60 kg less emissions of CO_2-equivalents. For the 15-15-15 products a difference of more than 130 kg CO_2-equivalents was calculated between urea, MOP and TSP versus CAN, MOP and TSP (**Table 2-5**). This clearly indicates that even for a given nutrient composition using the right raw materials can significantly reduce emissions. Previous studies showed that N_2O emission can be significantly reduced by using non-nitrate fertilizers, because high amounts of N_2O are emitted during the production of nitric acid, which is part of ammonium nitrate production (Laegreid et al., 1999; Brentrup et al., 2004b). Additionally it has been shown that emission for urea based fertilizers or urea containing blends can be reduced, when the urea N is stabilized using urease inhibitors (Snyder et al., 2009).

The overall emissions for the 15-15-15 FPTs are significantly lower. It is worth to be mentioned, that 6 kg nitrogen per functional unit (i.e. 300 kg complex fertilizer applied to 1 hectare arable land) has a broad impact on the greenhouse gas emissions, particularly for the complex fertilizer where the emission is nearly 130 kg CO_2-equivalents higher.

Table 2-5 Impact results for each impact category and for the different fertilizer product types for all life cycle stages for applying 300 kg of a 15-15-15 complex fertilizer (i.e. 15% N, 15% P_2O_5 and 15% K_2O). Statistically significant differences within each impact category are expressed in different letters based on a Tukey test ($p \leq 0.05$).

	Impact categories									
Fertilizer product type	**Climate change (kg CO_2-eq)**		**Fossil Fuel depletion (kg oil-eq)**		**Acidification (kg SO_2-eq)**	**Eutrophication (kg N-eq)**		**Resource depletion (kg Fe-eq)**	
Complex	432	c	45.1	c	1.92	1.69	b	0.030	b
CAN/MOP/DAP	410	b	30.7	a	2.16	1.72	c	0.016	a
CAN+MOP+DAP	412	b	30.7	a	2.36	1.72	c	0.017	a
Urea/MOP/TSP	391	a	41.3	b	2.08	1.63	a	0.017	a
Urea+MOP+TSP	392	a	41.3	b	2.27	1.63	a	0.018	a
CAN/MOP/TSP	522	d	50.2	d	2.21	1.82	d	0.018	a
CAN+MOP+TSP	524	d	50.2	d	2.40	1.82	d	0.019	a
RSE*	3.7		0.033		ns+	0.00018		0.0032	

/// all three components are blended and the final blend is applied in one application
+++ the three components are applied in three application steps
*Residual standard error
+not significant

Production and application are the most important sources for greenhouse gas equivalents (**Figure 2-3**). N_2O emissions during these two steps in the fertilizer supply chain represent 50% and more of all emissions in these impact category, followed by CO_2 emissions during production, which is particular important for urea based SN and BB. Due to the different production process N_2O emissions at the fertilizer plant play a minor role for urea (EFMA, 2000g). The transportation systems represent only about 1 to 3% of the overall emission of greenhouse gases; **Figure 2-3**).

It has to be kept in mind that in our LCA study CO_2 absorption by growing plants was not considered (see **Figure 2-2**). Therefore, the overall emission of CO_2-equivalents in other agricultural LCA studies can be much lower. It is obvious, that the emission of greenhouse gases clearly is a function of the amount of nitrogen used in crop production, which is confirming earlier studies conducted by Brentrup et al. (2004b), Brentrup et al. (2000) and Charles et al. (2006). In conclusion high nitrogen use efficiency and lower nitrogen input might be key factors to minimize the sustainability gap. One approach could be the so-called “sustainable intensification”, which aims for higher output with the same or a lower environmental impact, e.g. new crop varieties achieving higher yields with same inputs or having a higher nitrogen use efficiency (Garnett et al., 2013). Furthermore SN and BB fertilizers offer additional flexibility enabling the farmer to decide on all three major nutrients on a field-to-field basis. Combined with the use of the right basic materials, further improvements in the reduction of greenhouse gases in agricultural production seem possible.

Fossil fuel depletion

Within the fertilizer production and supply chain, 47 to 58 kg (for the 17-5-13; **Table 2-4**) and 31 to 50 kg (for the 15-15-15; **Table 2-5**) oil-equivalents are required, indicating that the higher N content in the 17-5-13 leads to higher requirement of oil-equivalents. Particular the use of natural gas in the production of different nitrogen fertilizers plays an important role. In CAN nitrate and ammonium are combined as nitrogen sources, while DAP contains only ammonium and urea consists of $CO(NH_2)_2$) as nitrogen form. All these different N forms are produced in different ways (see EFMA, 2000a, b, c). Therefore, the variation between the FPTs can be explained with the differences between the diverse forms of nitrogen. As the production of CAN uses the largest volume of oil-equivalents (EFMA, 2000a) in both cases the FPT containing the highest amount of CAN (CAN, MOP and TSP; see **Table 2-2**) has the greatest values in this category. Interestingly for the 17-5-13 N-P-K formula the urea based FPTs lead to significant reduced values, while for the 15-15-15 the DAP based FPTs are the best choice in the context of fossil fuel depletion (**Figure 2-4** and **2-5**). One option to lower the demand for fossil fuels used for fertilizer production (and the significant agricultural dependency on natural gas) might be the use of biogas based on non-food materials (e.g. organic manures, maize silage) as process gas in fertilizer production. However, this can lead to an increased emission in the impact categories acidification or eutrophication (Ahlgren et al., 2010).

Acidification

The AF net emissions vary from 1.20 to 2.40 kg SO_2-equivalentes (**Table 2-4** and **2-5**). Emissions are in general higher for all FPTs with a balanced nutrient composition (15-15-15; 1.92 to 2.40 SO_2-equivalentes) than for the 17-5-13 products (1.20 to 1.56 SO_2-equivalentes). One explanation might be that transportation is the most important factor for the impact category acidification (standing for more than 60% of all emissions in this category), and that the 15-15-15 FPTs have always higher freight weights then the 17-5-13 FPTs (**Table 2-2**).

Combustion of diesel has the highest impact in the acidification category (Spirinckx and Ceuterick, 1996). Particularly transportation processes with agricultural machinery and trucks create high emissions leading to higher acidification values for SN due to the multiple applications (i.e. more tractor based transportation). Up to 55% of all SO_2-eqvivalent emissions can be related to truck and tractor transportation for SN fertilizers. For the other two FPTs (CF and BB) only up to 45% are related to truck and tractor transportation. Production of complex fertilizers also leads to a high amount of emissions in the acidification category. It is worth to be mentioned, that the variation in this impact category is relatively high due to considerable differences in truck or tractor transportation. With nearly every kilometer of truck or tractor transport acidification is increasing, while transportation routes with a higher share of ship or train transportation lead to lower acidification values.

Other LCA studies have shown that the use of urea as nitrogen source leads to much higher acidification (e.g. Brentrup et al., 2000; Brentrup et al., 2004b) which could not be confirmed in our study. These differences can be explained by the system boundary used in our study, which ended directly after fertilizer application at field level and did not take into account the transformation processes of the different N forms on the soil surface or within the soil.

Eutrophication

Emissions associated with the impact category eutrophication range from 1.17 to 1.82 kg N-equivalents (**Table 2-4** and **2-5**) taking losses of NH_3, NO_x, NO_2 and NH_4 into consideration. In general, for all 15-15-15 FPTs a slightly higher eutrophication value was calculated (1.63 to 1.82 kg N-equivalents compared to 1.17 to 1.60 N-equivalents for the 17-5-13). This might be due to the different production process of the complex fertilizer, the longer transportation distances to the south-west region and/or the higher losses after application of the 15-15-15 product.

For this impact category, the emissions during fertilizer application at field level are the dominant factor. At that stage of the supply chain, losses to the environment (i.e. into surface waters and shallow groundwater bodies) have a clearly higher impact, compared to the other steps within the chain. However, some losses take place during production (for the 17-5-13: 3 % for the complex fertilizer, 15 to 25% for the other FPTs; for the 15-15-15: nearly 40% for all FPTs [Davis and Haglund, 1999]). Although fertilizers are held responsible to be the main factor for that category, compared to climate change and fossil fuel depletion these emissions are relatively low. Nevertheless, it has to be kept in mind that water bodies (especially small lakes and ditches) are much more sensitive to environmental impact than air.

As the FPTs within each group (17-5-13 versus 15-15-15) have an equal nutrient content, the difference in the emissions must have another explanation as the pure nutrient content. One explanation might be the differences between the different nitrogen fertilizers. Urea is associated with very low emissions during production (EFMA, 2000g) and therefore the overall emission is significantly lower compared to the other FPTs. Although the differences are statistically significant (only for the 15-15-15) due to the relatively small residual standard error, these differences are not relevant from an environmental point of view.

The values calculated for the impact category eutrophication seem to be quite low compared to other studies (Ahlgren et al., 2010; Spangberg et al., 2011). It has to be kept in mind that in our calculations nutrient uptake by crops as well as run-off or leaching losses during and particularly after the cultivation period were not considered. According to Blengini and Busto (2009), Martinez-Blanco et al. (2011) and Torrellas et al. (2012) mineral fertilizer production shows relatively large impacts in the eutrophication category, but this cannot be confirmed in our study with our system boundaries.

Resource depletion

Overall the values in the impact category resource depletion are rather small. For the 17-5-13 on average only 0.013 kg Fe-equivalents are calculated, while for the 15-15-15 it is about 0.018 kg Fe-equivalents. For the category resource depletion the production and transportation processes dominate the outcome of the calculation, while the use of minerals, such as phosphate rock and potash salts, are highly relevant. Especially phosphorus is in the focus of public debates, because the worldwide phosphate resources are shrinking considerably (Syers et al., 2008; Goedkoop et al., 2009; Dawson and Hilton, 2011). Additionally some minerals (like iron, platinum, silver or titanium) are needed in diesel or oil production and therefore take effect within the transportation process (Umweltbundesamt and Öko-Institut, 2016). The residual standard error is relatively low, so no statistical differences could be detected for the 17-5-13 (**Table 2-4**). For the 15-15-15 statistical significant differences were found, but they seem to be more random then coming from a ”real” effect. In general the 15-15-15 FPTs show higher resource depletion values because of the higher P content (30 kg per functional unit). Even if the phosphorus use per year is rather small, the extensive use of phosphate, combined with the growing world population and the diet shift for many people especially in developing countries, can lead to a bottleneck in phosphate availability (Neset and Cordell, 2012). Therefore, the use of phosphate in agriculture should always be well balanced and alternative resources as phosphate source (e.g. P containing sewage sludge) should be considered (Neset and Cordell, 2012; Syers et al., 2008). Additionally, a diet shift in developed countries, like Western Europe, towards a lower meat consumption can lead to a reduction in the phosphorus use in kg per person and year (Meier and Christen, 2012).

3.3.3. Scenario analysis

For the overall scenario analyzes corresponding datasets for SN and BB were pooled, because of minor differences in the impact assessment in the climate change category. The reduction of N_2O during the production of fertilizers can substantially reduce the emissions of CO_2-equivalents, which leads to different results compared to the baseline LCA.

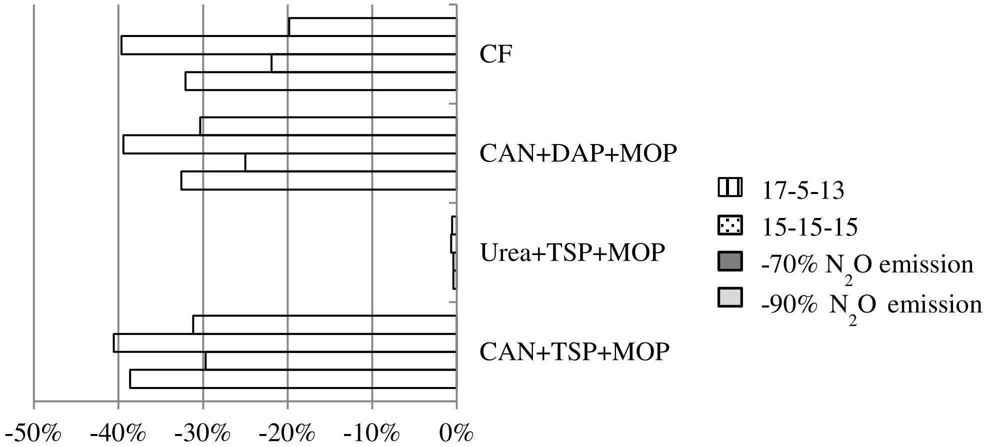

Figure 2-4 Relative reduction of CO_2-equivalents for the impact category climate change. Scenario calculations for a reduction of N_2O emissions during production of 70% and 90% (reference is based on N_2O emission for European fertilizer plants in 1999 [Davis and Haglund, 1999] and assumptions from Wood and Cowie [2004]). For fertilizer with the nutrient composition 17-5-13 or 15-15-15; CF: complex fertilizer; CAN: Calcium ammonium nitrate; MOP: Muriate of potash; DAP: Diammonium phosphate; TSP: Triple superphosphate.

Urea emits nearly no N_2O during production (**Figure 2-3**; Davis and Haglund, 1999; EFMA, 2000g) and therefore no improvements by reducing the N_2O emissions can be achieved (**Figure 2-4**). In other words, even under current European fertilizer production standards, urea should be used with special care and losses to the environment should always be avoided. For urea new techniques reducing the CO_2 emissions during fertilizer production and reducing the losses to the environment after application through stabilizing urea-N by using urease and/or nitrification inhibitors might be an option (Bellarby et al., 2008).

A reduction of N_2O emissions during production leads in all other cases to relatively large effects on the emissions of CO_2-equivalents. The climate change impact can notable be reduced because the global warming effect of N_2O is significantly higher compared to CO_2 (298 times higher; IPCC, 2007) or other greenhouse gases.

Assuming a 90% reduction in N_2O emission all 17-5-13 FPTs expect urea emit around 180 to 240 kg CO_2-equivalents less, representing a reduction of about 40% (**Figure 2-4**). Even a reduction by 70% N_2O during production leads to a total decline of 30% of the emission of CO_2-eqivalents compared to the baseline scenario. For the 15-15-15 FPTs the reductions in the category climate change are smaller, because the N_2O emissions in production are less important in the baseline scenario. Emissions of N_2O are mainly associated with the production of nitrogen fertilizers and the 15-15-15 contains 6 kg less nitrogen per functional unit so only an overall reduction of 24 to 38% can be achieved (i.e. a reduction of more than 200 kg CO_2-equivalents are possible for all FPTs containing CF or CAN). A 70% N_2O reduction during N production leads to similar results (i.e. reductions range from 20 to 25%).

Overall this scenario analysis can be used to adopt the results of our studies better to the actual situations in European fertilizer production. The reduction of N_2O losses to the atmosphere during fertilizer production already achieved due to the implementation of new catalyst filter technology in recent years has a great effect on greenhouse gases emissions in the fertilizer supply chain. However, up to now this new technical development is practically only implemented in European fertilizer plants, while nearly half of the fertilizer used in Europe is sourced from plants outside Europe (Fertilizer Europe, 2013) with techniques more comparable to the European average in the 1990s. As a consequence fertilizer production inventory assessments for plants in other regions of the world are absolutely necessary, because if best production techniques could be implemented worldwide, the overall environmental impact of N containing mineral fertilizers could be much lower. Furthermore, our investigation shows that the data source is a very important factor. The availability of up-to-date emission inventory data for fertilizer production is of foremost importance, because almost all agricultural and horticultural LCA studies are still using data collected in the period prior to 2000 (e.g. Davis and Haglund, 1999; Jenssen and Kongshaug, 2003; Wood and Cowie, 2004). This is especially relevant as the European production techniques have changed significantly from that date on (IFA, 2012).

2.4 Discussion and conclusions

The purpose of doing a LCA for different FPTs was to determine how diverse forms of fertilizers may alter the environmental impact. Our study was conducted to provide reliable data on the environmental burden associated with the use of muriate of potassium (MOP), diammonium phosphate (DAP), triple super phosphate (TSP), calcium ammonium nitrate (CAN) or urea as components for a single nutrient or bulk blend fertilization strategy compared to complex fertilizers.

Fertilizers are known to have considerable environmental impacts (e.g. Brentrup et al., 2004 b; Martinez-Blanco et al., 2011). However, as shown in this study different FPTs can have a substantial effect on the sustainability of agricultural systems. This study demonstrates that choosing the most efficient raw materials for FPTs can reduce emissions up to 20% compared to the worst alternatives. This is especially important for the impact categories climate change and fossil fuel depletion, the most important categories when evaluating the fertilizer supply chain. In this context the nitrogen content plays a very important role. Having a lower nitrogen content, the 15-15-15 FPTs have a lower environmental impact in the relevant categories climate change and fossil fuel depletion compared to the 17-5-13 FPTs. On the other hand transportation distances are more important for the acidification category than the form of fertilizers, while for the category eutrophication the P content of fertilizers play an important role. Because of its relatively low impact, resource depletion seems to have at the moment, no relevance for LCA focusing on the fertilizer supply chain.

From a worldwide perspective, urea is the most relevant nitrogen fertilizer. In general urea has the lowest price per unit N on the market and fertilizer purchasing by farmers is mainly price driven (Fertilizer Europe, 2013). However, the scenario analysis showed that other nitrogen fertilizers (e.g. CAN) can be more beneficial from an environmental point of view if they are produced with the best available technique. Additionally, high N use efficiency in plant production with an overall lower nitrogen input seems to be one of the key factors to close the sustainability gap. Improved fertilizer products (e.g. stabilizing the nitrogen in urea based products by urease inhibitors [Gioacchini et al., 2002]) and using better application techniques (e.g. crop based sensing technologies for in-field variable spreading of fertilizers [Auernhammer, 2001; Olfs, 2009; Zhang et al., 2002]) will allow reducing undesirable losses into non-agricultural ecosystems.

There is evidence that market shares for bulk blend fertilizers in Germany and other European countries will increase (Fertilizer Europe, 2013). Blending sites have to be large enough to cover investments of agro dealers, but transportation distances have to be considered as well. As shown, expanded truck and tractor transportation can lead to less favorable LCA results, especially in the acidification category. Bulk blend fertilizers can be used with a good adaptation to soil and crop conditions, which is not always the case for complex fertilizers with a fixed N-P-K formula. Most farmers tend to buy price driven more or less ignoring the likely impact on the environment. Further regulation might play an important role for reducing the overall emissions in agriculture. Additional research focusing on the total impact of fertilizer types and forms are needed to give adequate advice. Further comparisons with a greater number of nitrogen forms and even with organic nitrogen sources are desirable. In combination with recent data of fertilizer production from all over the word, this will enable novel insights into fertilizer use and the influence of fertilizer on the environmental impact of agricultural systems.

3. Where we go: Eco-innovations in the German fertilizer supply chain: impact on the carbon footprint of fertilizers

Chapter 3 answers research question 2:

To what extend do eco-innovations reduce the carbon footprint of fertilization?

3.1 Introduction

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 that only 18% to 49% of the fertilizer nitrogen applied is taken up by crops, while the remainder is lost by runoff, leaching or volatilization (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

This chapter is based on the following manuscript: Hasler, K., Omta, S. W. F., Bröring, S. & Olfs, H.-W. Eco-innovations in the German fertilizer supply chain: impact on the carbon footprint of fertilizers. Submitted to Plant, Soil and Environment.

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, 2016a). 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 J. et al., 2009; Ahlgren et al., 2010). This finding is particular relevant because N_2O has in a 100-year timeframe a 298 higher global warming potential than CO_2 (IPCC, 2007).

To improve sustainability in agriculture without losing the possibility of using mineral fertilizers, an option could be the adoption of innovative agricultural practices and techniques, further entitled as eco-innovations (Spiertz, 2010). Eco-innovations are innovations which aim to improve the production, application or exploring of a good that is novel and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the 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 a 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 a 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 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, we extended the carbon footprint calculations 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 in rice cultivation and from ruminant livestock (Snyder et al., 2009), which are not relevant for our study on the German fertilizer supply chain.

Additionally we use 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 reasons 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. Additional 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 furthermore 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 fertilizer 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.

3.1.1 Studied eco-innovations

Stabilized nitrogen fertilizer

Developed in the 1950ies, stabilized nitrogen fertilizers (SNF) 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 that chemically block or at least delay the transformation of urea/ammonium nitrogen into nitrate nitrogen (Watson and Laughlin, 2010). 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 has been shown that 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 favorable leading to increased N_2O fluxes (Jambert et al., 1997; Hao et al., 2001; Scheer et al., 2008; Aguilera et al., 2013). 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 1970ies 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 greater control over nutrient availability for the crop (Hagin and Lowengart, 1995).

FG serves 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 fertilizer 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-fam 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 they can help to maintain organic farming in areas with low or no livestock (planted based materials). 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.

3.2 Methods

3.2.1 General framework for the carbon footprint calculation

To calculate the carbon footprint we used the definition of Wiedmann and Minx (2008), who 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 CO_2 emissions our calculation were extended to a life cycle assessment (LCA) approach based on the ISO standard (ISO International Standard, 2006) including CO_2 and N_2O emissions. Because our carbon footprint calculations were focused on the German fertilizer supply chain and mainly mineral fertilizers methane emissions were not considered (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 CO_2 equivalent for CO_2 and 298 CO_2 equivalents for N_2O. General it was assumed that an application of 125 kg nitrogen per hectare as average ground fertilization for common agricultural systems 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 emission 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).

Mineral fertilizer production

Basic data for the GHG emission of mineral fertilizer production and application where 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 can be found in **Figure 3-1** (EFMA, 2000 a,b,c,d).

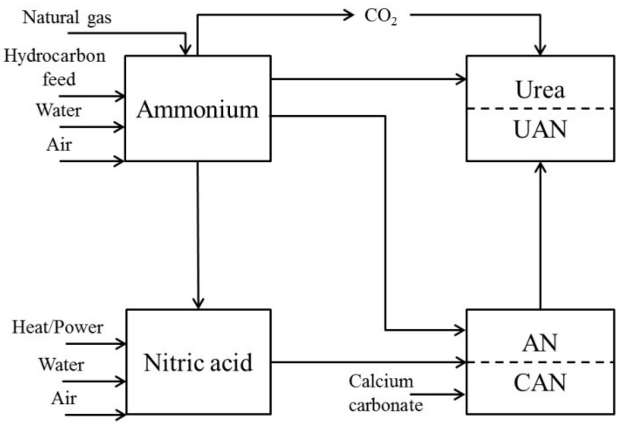

Figure 3-1 Flow-chart of mineral fertilizer production with natural gas as feedstock (UAN: Urea ammonium nitrate; AN: Ammonium nitrate; CAN: Calcium ammonium nitrate).

Due to new production technologies N_2O 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 fertilizer is produced and traded with a worldwide trading network, we assumed that for the nitrogen fertilizer mix offered in Germany less N_2O is emitted during the production process. We used an average value of 70%

for the N_2O emissions compared to the values listed in the above mentioned publications, leading to a N_2O emission of 0.000036 kg per kg urea and up to 0.00116 kg per kg CAN.

Transportation

Since fertilizers are both produced within Germany and imported from other regions, we assumed a mixed transportation (ship 35%, train 35% and truck 30%) over a mean distance of 700 kilometers for all mineral fertilizer products applied in German agriculture. Additionally a 100 kilometer 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).

Emissions from mineral fertilizer during crop cultivation

To estimate the N_2O emission during field cultivation emission from mineral fertilizers applied to a crop during the cultivation period an emission factor of 4.65 kg CO_2 per kg applied nitrogen was used (IPCC, 2007). Additionally an average of about 3.6 kg of lime per ha has to be applied for each kg nitrogen to balance the acidity resulting from nitrogen turnover in soils and nitrogen uptake by plants (Synder et al., 2009). Application of lime results in an average addition of 0.22 kg CO_2 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 ×0.22= 0.84 kg CO_2 per kg of nitrogen applied.

When producing urea CO_2 reacts with NH_3 to form the urea molecule ($CO(NH_2)_2$) resulting in a negative carbon footprint (i.e. atmospheric CO_2 is fixed). However, after field application this CO_2 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 CO_2 per kg of urea-nitrogen applied. This source category is included because the CO_2 removal from the atmosphere during urea manufacturing is estimated in the Industrial Processes and Product Use Sector (IPCC, 2006; Synder et al., 2009).

Furthermore indirect N_2O emissions from nitrogen leaching/runoff were estimated with the following equation (IPCC, 2006):

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

where F_{Fert} presents the annual amount of mineral or organic fertilizer nitrogen applied in kg nitrogen per year, $Frac_{leach}$ is the 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, EF_2 represents the emission factor for N_2O emissions from nitrogen leaching and runoff in kg N_2O-N per kg nitrogen leached and runoff.

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 et al. (2012) investigated the effects of UI and of a double inhibitor (UI + NI) on the N_2O emission following urea application in perennial field studies. According to these studies, the application of urea with UI alone reduced the N_2O 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 CO_2 emission. Weiske et al. (2001) examined the CO_2 and N_2O emission of ammonium sulfate nitrate combined with NI. In this field study the N_2O emission were reduced by 37%, and the CO_2 emissions by 7%. We used data from these field studies because they covered more than one cultivation period with different crops, as Bouwman et al. (2002) pointed out, that the period covered by the measurements strongly determines the amount of fertilizer nitrogen lost as N_2O.

Fertigation

For the GWP assessment of FG we used a similar data set as for common mineral fertilizers in combination with emission data of Scheer et al. (2008), Kennedy et al. (2013) and Abalos et al. (2014), 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 N_2O emissions leading to a lower N_2O emission factor (0.8-0.9% N_2O 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 CO_2 emissions due to fertigation. Abalos et al. (2014) reported that the CO_2 emission during field cultivation with melons plants was enhanced by 9% for urea and 39% for calcium nitrate. All emission data were additionally compared with ammonium nitrate in FG. These data were gathered from a meta study comparing different irrigation systems (drip, furrow, rainfed) in Mediterranean climates (Aguilera et al., 2013). Production of the irrigation and its transportation was not taken into account, because we assumed, that FG only takes place in regions were irrigation is a standard measure in all cultivation systems.

Secondary raw material fertilizers

For SRMF we focused on feather meals, meat-and-bone meals and leguminous crops meals. We did not consider compost, sewage sludge or other similar biosolids because of their rather low nitrogen content and their very poor short term nitrogen availability (**Table 3-1**). The calculations for the three different FRSM materials were based on data extracted from the ProBas database (Umweltbundesamt and Öko-Institut, 2016).

Table 3-1 Characterizations for SRMF products considered for the carbon footprint calculation (based on data from Choi and Nelson (1996), Gutser et al. (2005) and Hartz and Johnstone (2006)).

Basic materials	Nitrogen content ($kg\ N\ t^{-1}$)	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

[1]MFE: mineral fertilizer equivalents (according to Gutser et al. 2005).

Feather meals

As starting point for our calculations the production of fattened chicken and their transportation to a slaughterhouse were taken into account. We 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 CO_2 and 0.0245 kg N_2O 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 normal 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, 2016b). Finally the production of one kg feather meal results in the emissions of 0.135 kg CO_2 and 0.001375 kg N_2O. Furthermore we included transportation of the feather meals to farmers and application in the field (150 km mixed transportation with trucks and tractor). Finally we assumed that the produced feather meal has an average nitrogen content of 130 kg per ton and a short term mineral fertilizer equivalent (MEF) of 60%. MEF comprise the short term nitrogen implementation of an organic material. The direct utilization in the year of application is supposed to be relatively small, because of the slow-release characteristics of organically bound nitrogen (Gutser et al., 2005). 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 like game meat, rabbits or ducks were not taken into account. We 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 assumed, that the residues of the meat production of different animals (pig, poultry and beef) in Germany result in 2.17 million tons (**Table 3-2**). 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 CO_2 and 0.0027 kg N_2O per kg ready to use meat-and-bone meal. The production was assumed to take place in Germany or bordering states. GHG emissions of meat production can be found in **Table 3-2**. As process power the normal German electricity mix (see above) was taken into account.

Table 3-2 Meat production capacity, production for human consumption, residues and its CO_2 and N_2O emission for meat-and-bone-meal production in Germany (Umweltbundesamt and Öko-Institut 2016).

	Production capacity in Germany (kg year^{-1})	Meat production for human consumption* (kg year^{-1})	Production residues (kg year^{-1})	CO_2 emission from residues (kg year^{-1})	N_2O emissions from residues (kg year^{-1})
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 meal	-	-	2,170,000	1,226,710	5938

*BMEL (2016)

Additionally we included 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). 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^{-1} 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 we 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 emissions of 0.136 kg CO_2 and 0.0000399 kg N_2O (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. We expect that the considered leguminous crop meals have an average nitrogen content of 50 kg nitrogen t^{-1} and a short term MEF of 40%. Consequently 6250 kg leguminous crop meal can replace 125 kg nitrogen.

3.2.2 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 capacitates 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 N_2O emissions during fertilizer production was evaluated. With the use of new catalytic converter and filtering technologies N_2O 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 **Table 3-1**) and therefore higher amounts of SRMF products are necessary to compensate mineral fertilizer.

3.3 Results

Carbon footprint of mineral fertilizers

Emissions of CO_2 during production and N_2O 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 1300 kg for AN up to 1460 kg CO_2-equivalents for UAN (**Figure 3-2**). About 56% of the CO_2-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 CO_2 emissions of urea and UAN are much higher during the cultivation period.

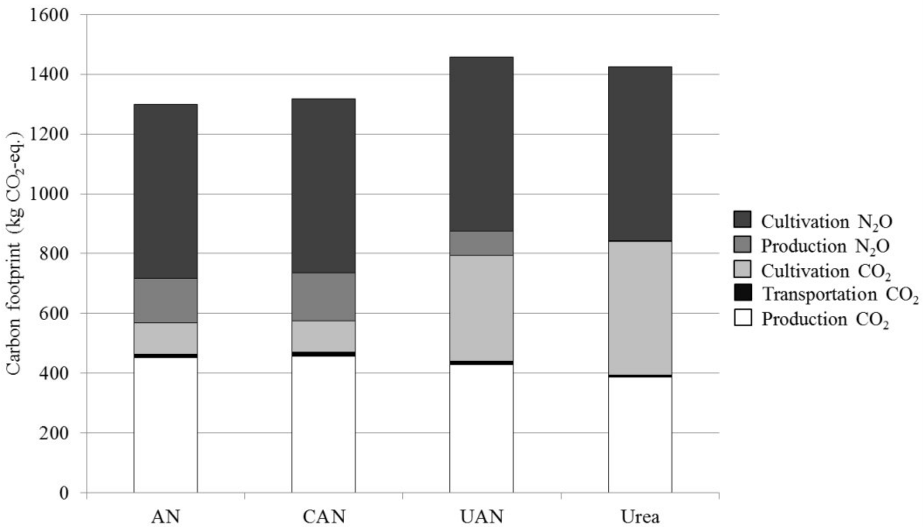

Figure 3-2 Carbon footprints of different mineral fertilizers calculated for one cultivation period (AN: Ammonium nitrate; CAN: Calcium ammonium nitrate; UAN: Urea ammonium nitrate).

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. Urease inhibitors seem to be less effective (carbon footprint: 1420 kg CO_2-

equivalents) compared to a combination of urease and nitrification inhibitors (carbon footprint: 1340 kg CO_2-equivalents; **Figure 3-3**).

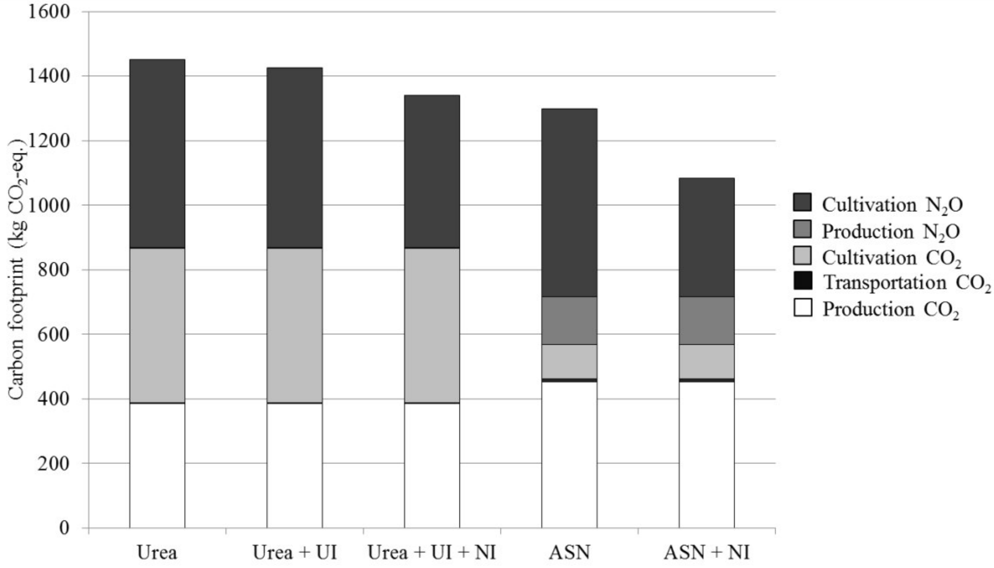

Figure 3-3 Carbon footprint of different mineral fertilizers and the respective SNF products for one cultivation period (UI: urease inhibitor; NI: Nitrification inhibitor; ASN: Ammonium sulfate nitrate).

The addition of the nitrification inhibitor dicyandiamide to ammonium sulfate reduces the carbon footprint by 17% from 1291 kg CO_2-equivalents to 1076 kg kg CO_2-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 extend for urea (- 20%; **Figure 3-4**). Especially N_2O emissions during the cultivation period are lower, while all CO_2 and the N_2O emissions during production are similar to conventional mineral fertilizer.

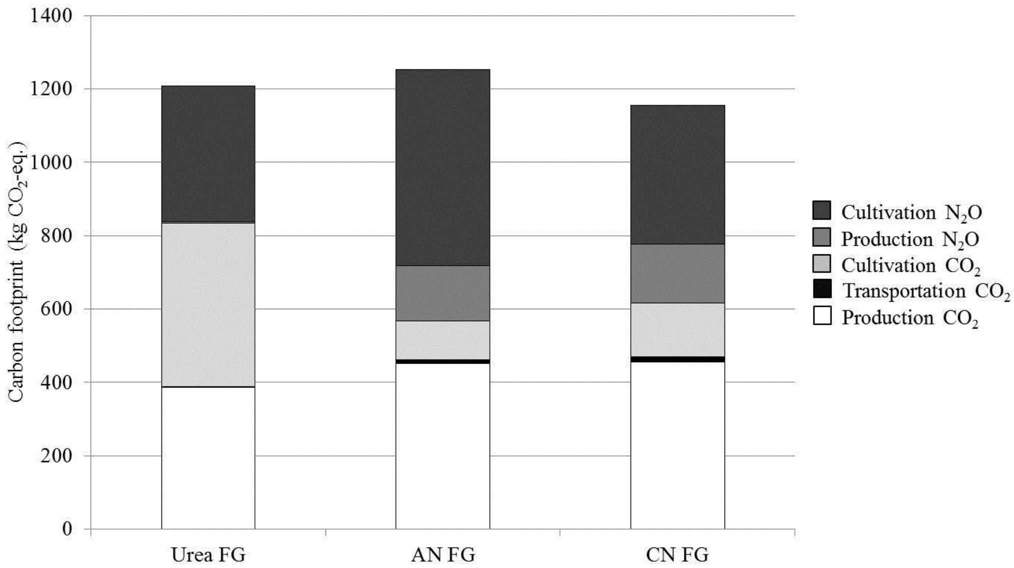

Figure 3-4 Carbon footprint of different mineral fertilizers applied via irrigation for one cultivation period (CN: Calcium nitrate; AN: Ammonium nitrate).

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 3-5**). 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 CO_2-equivalents) the carbon footprint calculation for feather meals and leguminous crops meals resulted in 10-20% higher values (1621 kg CO_2-equivalents and 1608 kg CO_2-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 CO_2-equivalents.

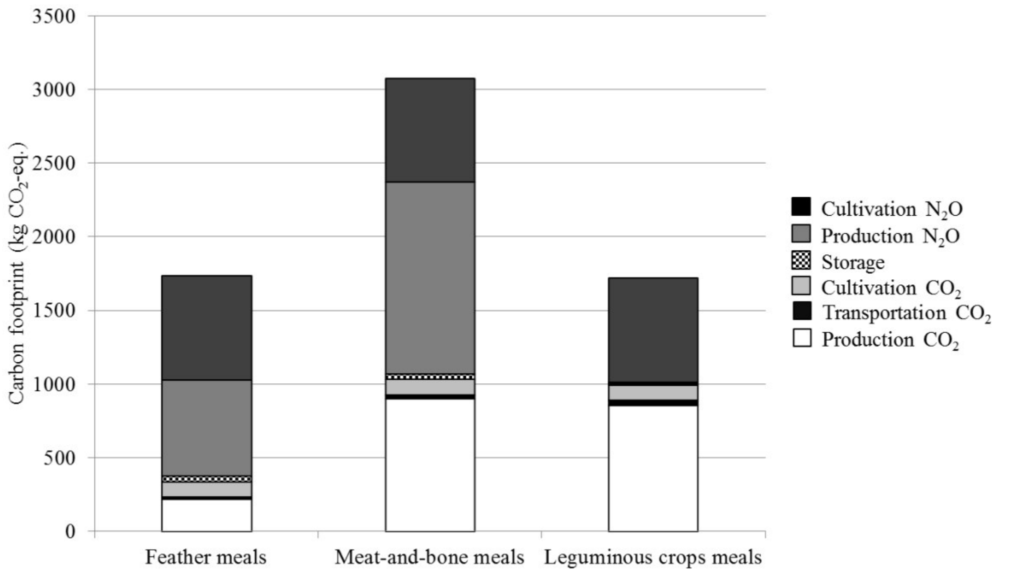

Figure 3-5 Carbon footprints of different secondary raw material fertilizers.

3.3.1 Sensitivity analyses and uncertainty of the carbon footprint assessment

The sensitivity analysis (**Table 3-3**) reveals that the changes in transportation distance only have little impact on the final results. On the other hand changes in the N_2O 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.

Table 3-3 Changes (%) in the carbon footprint based on a sensitivity analysis (MFE: mineral fertilizer equivalents according to Gutser et al. (2005); AN: Ammonium-nitrate; UI: Urease inhibitors; NI: nitrification inhibitor; ASN: Ammonium sulfate nitrate).

	Transportation distance (+50%)	N_2O emission during fertilizer production (-90%)	very low short term MFE (SRMF)*
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

*see **Table 3-1**

3.4 Discussion and conclusions

Emissions due to fertilizer application in crop production significantly influence the carbon footprint of agriculture production. However, essential plant nutrients cannot be substituted by other materials and nutrient exported via harvested products or losses from the soil-plant system (e.g. nitrate leaching, ammonia volatilisation, N_2O 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 Germany 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. We used the IPCC emission factor for our calculations even though several studies showed that N_2O emissions for different fertilizer sources/types (e.g. urea vs CAN; Bouwman et al., 2002) may vary substantially. However, mostly these differences are 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 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 normal mineral fertilizers an extension of the functional unit to finished product (e.g. one kg wheat) 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, due to irrigation and the soil moisture conditions for N_2O production after fertilizer application are more favorable (Jambert et al., 1997; Hao et al., 2001; Scheer et al., 2008; Aguilera et al., 2013) and therefore a strong stimulation of the N_2O 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 N_2O 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, 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 CO_2 or N_2O 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 normal mineral fertilization. SNF are much higher in price than existing mineral fertilizers and therefore gaining higher market shares will be unlikely as long as normal 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 CO_2 and N_2O emissions. SRMF is an alternative for waste disposal and in addition nutrient cycles are closed, but 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. Due to the fact that knowledge is very unevenly distributed in agricultural supply chains (Morgan and Murdoch 2000; Hasler et al. 2016) 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-innovation 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 CO_2 labels. However, up to now none of the existing consumer CO_2 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 actual 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 only implemented in European fertilizer plants and not representing the world wide 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 with new technologies produced mineral fertilizer would give a more reliable picture of present agriculture.

3.5.2 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 which are less volatile in pricing what might be directly related to the small market penetration. One explanation for the small market penetration most probably are higher costs (SNF and FG) or different sales and supply chain strategies (SRMF).

Overall SNF have the highest market share of all eco-innovations considered in our study for Germany, but still they have to be ranked as niche products. Because the German fertilizer statistic does not distinguish between normal and stabilized nitrogen fertilizers only estimates are available. About a decade ago it was assumed that stabilized fertilizers comprise 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 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 normal 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 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.

4. What we know: Drivers for the adoption of different eco-innovation types: A review.

Chapter 4 answers research question 3:

Have different types of eco-innovations different problems to diffuse throughout the fertilizer supply chain?

4.1 Introduction

World food production has rapidly grown during the last decades and now it 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 world population, the intensity of the production on agricultural land has to be significantly increased (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). However, unlike pesticide or other agricultural inputs, plant nutrients cannot be substituted by other products. Nevertheless, a better adoption of the necessary plant nutrients to the actual requirement and a better use efficiency can be reached with new fertilizer products (innovation) or better tailored application and cultivation methods (Tilman et al., 2002; Stehfest and Bouwman, 2006). Products, services or management strategies with the purpose to improve the environmental impact and the increasing economic value can be classified as eco-innovations (Kemp et al., 1998). Numerous eco-innovations have been developed in the fertilizer sector in the last decades, but none of

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them has seen a successful market adoption leading to higher market shares(Renni and Heffer, 2010; Hasler et al., 2016). Nevertheless, identifying the main reasons can help policy makers and other decision-makers to implement instruments which are effective and efficient enough to promote eco-innovations in the fertilizer sector (del Río et al., 2016). Numerous publications have reviewed the literature on firm-level determinates of eco-innovations (Díaz-García et al., 2015; del Río et al., 2016; Hojnik and Ruzzier, 2016). All reviews have identified main determines, like regulatory pressures, firm size or firm age. However, a company and a single farm are not in all cases completely comparable (Bossle et al., 2016; Hojnik and Ruzzier, 2016). Additionally classic business models, even models specific tailored to eco-innovations (Tsvetkova and Gustafsson, 2012; Hellström et al., 2015) are not sufficient enough to explain the low adoption of eco-innovations on farm level (Diederen et al., 2003). Here individual models explaining the innovation adoption like Rogers theory of innovation diffusion or Davis technology acceptance model are more suitable (Davis, 1989; Rogers, 2003). Therefore, as basic model for innovation adoption the technology acceptance model (TAM) was selected (Davis, 1989; Davis et al., 1989). This simple model for technology adoption was extended by external precursors, factors suggested by other theories and contextual factors. To our best knowledge, this is the first attempt to explain the low adoption of innovations within a sector not by only by frim specific factors, but on a more individual level, putting the farmer and therefore the innovation adopter, into the focus. Additionally this literature review combines the innovation adoption in agricultural supply chains with the lens of innovation typologies, to reach a better understanding of the reasons for the low adoption rates of eco-innovations. Therefore, the innovations found within this review are categorized to six cases: First the eco-innovations were divided into disruptive (changing the way of farming or fertilizer application; (Christensen et al., 2015)) or continuous (not changing the complete fertilizer management; (Hargadon, 1998)) innovations. Here we used the division of Garcia and Calantone (Garcia and Calantone, 2002) claiming that disruptive or, in their terms radical innovations, combining a new technology and a new market, making the adoption a much difficult task. Continuous or incremental innovations present only new features, benefits or improvements to existing technologies in existing markets. Or more precisely for the agriculture environments: disruptive innovations change the working process and the everyday situation, need new or advanced technology, information or support and are not easy to adapt to the existing management strategy (Markides, 2006); continuous innovations change only the yield or the quality of agricultural products, are easy to adapt and could face other acceptance problems (Boer and Gertsen, 2003). Afterwards, the reviewed publications were divided into different types of innovations. This division was made, because we assume that different eco-innovations types are facing specific difficulties in the innovation diffusion process, because of their various natures. In the fertilizer sector, mostly process innovations (for both disruptive (1) and continuous innovations (2)) product innovations (service (3) and goods (4)), organizational innovations (5) and other types of eco-innovations (6) can be distinguished. According to our best knowledge, this is the first attempt to review the innovation adoption literature by the characteristics and types of innovations in agriculture. Here the different characteristics of specific eco-innovations types had been used to come to more general conclusions of the eco-innovation adoption in the fertilizer area and the entire agricultural sector.

The remainder of this Chapter is structured as follows. Section 2 focuses on the analytical framework and give an overview about the theoretical approaches. Section 3 presents the systematic literature review, while results are discussed in Section 4 First, a basic description of the aggregated publications is performed, followed by more systematic descriptions for the five cases (disruptive process and other type of innovations, continuous process and product (services and goods) innovations). Finally, the paper closes with the syntheses of the main drivers fertilizer innovation adopted in general and for the specific environments.

4.2 Methods

To meet the challenges of global food security and the environmental impact of agriculture in a sustainable way requires the use of modern agricultural practices and a knowledge based approach (Spiertz, 2010). One solution to stop the continuing world food crisis might be the suggestion of a substantially greater use of fertilizer inputs. However, there is growing evidence that fertilizer use has already reached critical environmental limits, and that the aggregate costs in terms of lost or foregone benefits from environmental service are too high for the world to bear (Ruttan, 2002; Kitzes et al., 2007). With a higher farming intensity the environmental impacts on non-agricultural ecosystems will also increase. Especially the production and application of (nitrogen) fertilizer generate a high amount of greenhouse gas emissions and has high primary energy consumption during the production (Davis and Haglund, 1999; Brentrup and Pallière, 2008). Nevertheless, nitrogen is the most important mineral nutrient for agricultural production and an adequate supply is essential for high yield, especially with modern cultivars (Mulvaney et al., 2009).

Here the implementation of so called environmental or eco-innovations could solve a wide range of the above mentioned problems. Eco-innovations are defined as innovations that reduce the environmental impact or the use of natural resources (Kemp et al., 1998; Rennings, 2000; Ekins, 2010). This can lead to innovations targeting a more responsible application of fertilizers. A widely used definition is the one of Kemp and Pearson (Kemp and Pearson, 2008), who defined eco-innovation as production, application or exploring of a good or service, that is novel to a firm or user and which results, in a reduction of environmental risk, pollution and the negative impacts of resource use compared to relevant alternatives. Ekins (Ekins, 2010) even went one step further by mentioning eco-innovations as a change in economic activities that improves both the economic and the environmental performance of society. In the present review the focus lays on eco-innovations in the field of fertilization and plant nutrition. Here we are especially interested in the interaction between the innovation type and the drivers for the adoption. The overall goal is, elucidate factors driving concerning the adoption of eco-innovations. In the fertilizer sector, most eco-innovations are encircling a better adjustment of fertilization to the agricultural environment, closing nutrient cycles or to improve nutrient and cultivation managements (Renni and Heffer, 2010).

First, the main characteristics of eco-innovations were distinguished. By separating the innovations in disruptive and continuous innovations it was aimed to get a better understanding in the adoption process of more radical and less radical innovations. Disruptive innovations are innovations which create a new market or displace or disrupts existing markets (Christensen et al., 2015). Disruptive innovations tend to be produced by outsiders and entrepreneurs, rather than existing market-leading companies (Christensen, 2013). The business environment of market leaders does not allow them to pursue disruptive innovations when they first arise, because they are not profitable enough at first and because their development can be fundamentally different from the normal production process and can need different resources (Christensen, 2013). A disruptive process can take longer to develop than by the conventional approach and therefore risk associated to it is higher than by other forms of innovations (Assink, 2006). Continuous innovations are ongoing advancement of existing technologies or products. They do not fundamentally change the market dynamics and therefore they do not typically require end users to change in behavior (Law, 2016).

Furthermore, innovations can be divided into different types. This distinction between different innovation types has found to be essential, because the types have different characteristics and their adoption is not affected identically (Kimberly and Evanisko, 1981; Jansen et al., 2006; Damanpour et al., 2009). The variety of different innovation types is outstanding, the best known and widest study typology of innovations is the distinction between product and process innovations (Utterback and Abernathy, 1975; Kotabe and Murray, 1990). Edquist (Edquist, 2001) expands these two established typologies by including two types of product innovations ('in goods' and 'in services') and two types of process innovations ('technological' and 'organizational'). Whereby the technical process innovation compromise things such as customer services, logistics and procurement and organizational innovations thinks such as strategic planning, project management and employee assessment (Hamel, 2006). For the fertilizer supply chain the following four types of innovations could be distinguished as relevant: (1) Product innovation resulting in new goods or products, like stabilized nutrients, (2) product innovations resulting in new service options, like online diagnose tools for nutrient status, (3) process innovations, like advanced consultation which can be needed within a sustainable intensification, and (4) other types of innovations which have more than one specific characterization, like precision farming using new products, new services and new processes (Renni and Heffer, 2010; Hasler et al., 2016).

There are numerous models to describe technology acceptance and use, for example Rogers's theory of innovation diffusion (Rogers, 2003), the Concerns-Based Adoption Model (CBAM; (Fuller, 1969; Hall, 1979)) or the technology acceptance model (TAM; (Davis, 1989)). Because of its simplicity and frequent use, the TAM was used as model for innovation adoption in the context of this article (**Figure 4-1**).

The TAM bases on studies and models of empirical social sciences, especially the model of theory of reasoned action developed by Ajzen and Fishbein (Fishbein and Ajzen, 1977). Davis (Davis, 1989) and Davis et al. (Davis et al., 1989) thereof developed the TAM to provide an explanation that intended the acceptance of computer usage across a wide range of end-user. According to Straub (2009) Davis identified two perceived characteristics about new technologies which, in his belief, could predict the actual use. Those are the perceived ease of use (PEU) and the perceived usefulness (PU). However, because of its simplicity and attitude behavior gap, the TAM often fails to actually describe the way of innovation acceptance in agriculture (Flett et al., 2004; Vermeir and Verbeke, 2006; Rezaei-Moghaddam and Salehi, 2010). Additionally because of their specific nature, eco-innovations are facing more acceptance problems than other innovations. Here the classic factors pushing innovations like technology push or market pull mostly fail to fully explain the diffusion of eco-innovations (Frondel et al., 2008; Horbach, 2008; Horbach et al., 2012). Due to the external problems of eco-innovations, like the level of technological capabilities acquired through R&D activities, no strong impulses for eco-innovation creation from the demand side (Rehfeld et al., 2007) and the lack of knowledge transfer mechanisms and involvement in networks (Morgan and Murdoch, 2000; Demirel and Kesidou, 2011; Horbach et al., 2012), the traditional discussion of innovation economists has to be extended. King and He (2006) found in a meta-analysis several variables, which can improve the forecasting quality of the TAM without changing the simple characteristic of it. The inclusion of external precursors (Jackson et al., 1997; Venkatesh et al., 2000; Negro et al., 2007; Tey and Brindal, 2012), the incorporation of factors suggested by other theories, the inclusion of contextual factors (Straub et al., 1997; Venkatesh et al., 2000; Diederen et al., 2003) and the inclusion of consequence measures (Davis, 1989; Szajna, 1996; Davis and Venkatesh, 2004) are found to be most useful to describe the innovation adoption in a larger scale. For the agriculture sector, the inclusion of consequence measures (such as attitude, perceptual usage and actual usage) is only rarely investigated in scientific publications and was therefore excluded. (**Figure 4-1**).

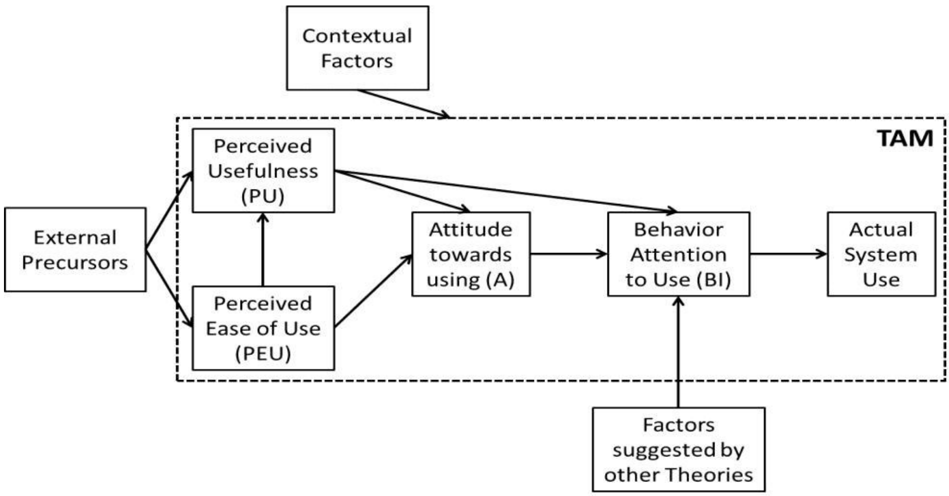

Figure 4-1 The technology acceptance model and its extension for the literature review.

1. The inclusion of external precursors such as situational involvement (like the involvement in external groups or co-operations; Jackson et al., 1997), pressure by regu-

lation (Diederen et al., 2003), observability (Marra et al., 2003; Tey and Brindal, 2012), quality of support (Aslan et al., 2007; Negro et al., 2007), information (Diederen et al., 2003; Negro et al., 2007) and compatibility (Zhang et al., 2002).

2. The incorporation of factors suggested by other theories that are intended to increase TAMs predictive power; these include expectation (Venkatesh et al., 2003), task-technology fit (Dishaw and Strong, 1999; Diederen et al., 2003), risk (Featherman and Pavlou, 2003), access to credit (Diederen et al., 2003) and market access (Diederen et al., 2003).
3. The inclusion of contextual factors such as gender, age, education, farm size and land-ownership that may have moderator effects (Straub et al., 1997; Venkatesh and Morris, 2000; Diederen et al., 2003; Venkatesh et al., 2003; King and He, 2006).

In the following section, the external precursors and factors suggested by other theories are shortly explained, starting with the external precursors:

- The involvement external groups' (like co-operations, organizations, advisory council or association) can be a good source and distribution of information, knowledge and application of new technologies or products (Jackson et al., 1997). External groups can provide there participations with external resources and regular meetings and can therefore stimulate farmers to try something new (Shiferaw et al., 2013).
- Regulations can stimulate the need to adopt certain innovations faster (Diederen et al., 2003; Hasler et al., 2016). Farmers need to see an improvement by using new methods and technologies. Therefore, the observability of the effects of these new methods or technologies on the yield, yield quality or harvest material is important for the acceptance (Marra et al., 2003; Tey and Brindal, 2012).
- The quality of support can have a strong influence on the eco-innovation adoption (Aslan et al., 2007; Negro et al., 2007). This is especially important for innovations with a more technical origin. Here the support must not only provide a platform for buying and selling, but also for learning, repair, assistance and training (Reichardt et al., 2009; Watcharaanantapong et al., 2014). Also the adoption of process innovations can be stimulated by a good technical or personal support (Mafongoya et al., 2006; Gowing and Palmer, 2008).
- Information and knowledge exchange can be strong precursor for innovation adoption (Diederen et al., 2003; Negro et al., 2007). According to Carlsson and Jacobsson (Carlsson and Jacobsson, 1997) it is essential to form an exchange of information throw-out a network to get a better understanding of innovations and therefore a higher willingness to expose innovations.
- Compatibility is especially important for innovations concerning more technical solutions with need to be fitted to the existing farm equipment (Zhang et al., 2002). Therefore, it plays a more significant role for disruptive innovations. New technologies or management systems raise definite expectation by the users, in this case farmers (Venkatesh et al., 2003).

Factors suggested by other theories can be outlined as followed:

- In this review expectations are mainly expressed in higher yields or better yield qualities (Batte and Arnholt, 2003; Busse et al., 2014), followed by the reduced use of fertilizers (Adrian et al., 2005) or less fertilizer costs (Marra et al., 2003). Therefore the variable expectation can be multi-dimensional. In order to regard that fact, we only include expectations regarding the yield and yield quality, because these are the main factors influenced by fertilizers.
- The variable task-technology fit can be a good trigger to describe the adoption of more disruptive innovations. If an innovation involves a large number of different technologies (e.g. IT, agricultural machinery, measuring devices), all these technologies need to be controlled by the farmer (Dishaw and Strong, 1999; Diederen et al., 2003). Here a better understanding of the underlining technology and a more open attitude towards new technologies can trigger a positive adoption. .
- Access to credit can stimulate more expensive eco-innovations with a potential in cost-saving in the near future (e.g. some precision farming technologies; (Diederen et al., 2003).
- Market access combines the fact, that an eco-innovation must be available for the user and the end-products, created with new technologies must be disposable on markets (Diederen et al., 2003).

4.2.1 Systematic literature review methodology

First, we limited our search to fertilizer literature using the web-based search engine ISI Web of Knowledge(SM). Topic search (TS) was used to identify publications that refer to fertilizer in title, abstract, author, keywords and keywords plus®. The reach was further narrowed down to English language articles including peer-reviewed research papers, review papers, proceeding papers and book chapters published, between January 1945 and January 2017. That search resulted in 58,650 publications in the field of fertilizer and plant nutrient. Additionally we include papers concerning precision agriculture or precision farming, because this is one major development in the area of plant nutrient and fertilizer application in the last decade. Here the search results in 2389 publications. We now combined these two studied areas with the concept of innovation adaption, diffusion, transfer and acceptance. A combination of the innovation keywords and the fertilizer or the precision agriculture and precision farming topic results in 100 publications. By screening references in the selected documents and applying ‘snowballing’, 48 documents were added to the final review. Papers on precision farming were only included if they have a major focus on fertilizer splitting, application, reduction or use. General precision farming papers were excluded from this review. After screening the abstracts of the 148 publications, 9 precision agriculture publications and 48 publications with fertilizer as topic were exclude from the review because of their limited relevance (e.g. urine separation, soil fertility in general, improved seeds or irrigation) coming to a total of 91 publications. All publications were evaluated by the main eco-innovations, publication type, the publication year, the journal, the country of research, the first author background and the main drivers.

4.3 Results of the systematic literature review

4.3.1 Different eco-innovations in the fertilizer sector

All analyzed 91 publications have a clear perspective on innovation in the fertilizer or plant nutrient area. Some of them are only changing single production steps, some change the whole way of farming. In the following, the main eco-innovations are shortly outlined. These are namely: (1) conserve farming (2) diagnose tools for nutrient status (3) fertigation (4) fertilizers made from secondary raw materials (5) intercropping with (leguminous) crops (6) knowledge training (7) nanotechnology (8) new cultivation methods (9) nutrient management technologies (10) precision farming (11) stabilized nutrients (12) sustainable intensification. All these eco-innovations were divided according to their specific type. First they were split in disruptive and continuous innovations. An innovation was categorized as disruptive, if the farming management system needs to be changes, the technology used is modified and/or it requires a more or a more specific information flow, knowledge exchange or education. Additionally it was considered, that the existing supporting or trading system is not sufficient enough to fully support the adoption of these special innovations. Continuous innovations requires only minor changes in the farming management system, they are easy to integrate within the existing technology, supporting or trading network and only need a minimum of specific information, knowledge or education. Furthermore, all eco-innovations were split to their main characteristic, meaning if they are a process or product innovations or innovations of other types. Process innovations only change the process of, in our chase e.g. the application, but not other parts of the fertilization, product innovations represents new fertilizers products. Innovation of other types change the whole way of fertilizer usage and therefore mostly include more than one innovation characteristic. A high number of publications, classified as disruptive innovations, deal with new cultivation or farming methods regarding the application, use and management of fertilizers (e.g. (Akudugu et al., 2012; Loyce et al., 2012; Tey et al., 2014)). In developing countries, these new cultivation methods even estimate the pure use of mineral fertilizers. In more developed countries, the publications are aiming to come to new cultivation methods reducing the fertilizer input. All publications are circling around new ways of farming and crop production, with a higher technical input or a different training and service, wherefore all were categorized as disruptive innovations. Precious farming or precision agriculture is another widely published topic regarding eco-innovations in the fertilizer sector. Only publications with a focus on fertilizer application via precision farming were included in this review. Here especially the agricultural production in developed countries lies in the focus (e.g. (Adrian et al., 2005; Aubert et al., 2012; Watcharaanantapong et al., 2014)). These innovations are disruptive, because they need specific technology equipment and different types of fertilizers. The same holds true for conservative farming methods. Here the application of fertilizer and plant nutrients is a much more difficult and technical task, because of the different soil conditions and technical aspects, like impossible soil tillage after the fertilization. Therefore, the whole farming system must be adapted to the new farming management regime, including the purchase of new farming technic or (e.g. (Knowler and Bradshaw, 2007; Namara et al., 2007; Chauhan et al., 2012)). Another more disruptive innovation is the implementation of so called sustainable intensification in agriculture production. That is, the use of fertilizers and plant nutrients is higher at regions with high yields and yield potentials and lower in areas with a less optimal farming area. Consequentially, high productive systems are producing at the yield maximum and low productive systems as environmental friendly as possible. That could also mean to shift certain cultivars to better fitted areas making agricultural environments more specialized (e.g. (Tey et al., 2014; Ju et al., 2016)). One publication estimated the influence of nanotechnologies on the fertilizer use and production (Handford et al., 2015).

Many publications concern specific crops where the cultivation should be optimized with better fertilization strategies or new ways of fertilizers application (e.g. (Pandey, 1999; Simpson et al., 2013; Simpson et al., 2014)). These eco-innovations are classified as continuous process innovations. Product eco-innovations concerning the establishment of new goods all aims to lower the environmental impact of fertilization. Here in particular the stabilization of the nutrients in the soil, closing the nutrient cycles, or a more efficient use of the fertilizer nutrients are discussed (e.g. (Hasler et al., 2016; Herrera et al., 2016a)). Other publications have the use of mineral fertilizer in developing countries in the focus (e.g. (Lambrecht et al., 2014; Nin-Pratt and McBride, 2014)). Furthermore, diagnose tools for e better estimation of the crop nutrient status are evaluated by a number of publications (e.g. (Hayman et al., 2007; Zhang et al., 2016)). A well-established way to maintain soil fertility is the intercropping with, mostly leguminous, intermediate crops. In this review, many publications are concerned about optimizing these intercropping, especially in developing countries (e.g. (Mafongoya et al., 2006; Ajayi et al., 2007; Magrini et al., 2016)). Another, more service orientated eco-innovation can be the implementation of knowledge training methods for all members of the fertilizer supply chain (e.g. (Abate et al., 2016; Zhao et al., 2016)). Here best production technologies or information of specific innovations can be diffused to a large number of farmers, making fertilization more sustainable.

4.3.2 Results of the literature review

Table 4-1 Search results using topic search with ISI web of knowledge for fertilizer and precision agriculture publications and publications concerning innovation adoption.

	Fertilizer and plant nutrient	**Precision agriculture**	**Innovation adoption**
Search keywords	#1: TS=((fertilizer) or (fertiliser) or ("Plant nutrient") or (plant + nutrient) or (“Plant nutrition”) or (plant + nutrition))	#2: TS=("precision agriculture" or "precision farming")	Within #1 and #2: TS=(((Innovation) AND (Adoption OR Diffusion OR Transfer OR acceptance) or ((Eco-Innovation) AND (Adoption OR Diffusion OR

			Transfer OR acceptance)))
Number of results	58,650	2389	100 + 48 from a snowball search
Connection to the theoretical framework	Basic research setting to get information about the fertilizer and plant nutrient sector	Addition to the basic research setting, because many publications are not specific tailored to the word fertilizer or plant nutrient	Combination of the basic research setting and the extended TAM in order to come to more general conclusions
Range of pub. years	1946-2017	1994-2016	1993-2017
Avg. pub. per year (1994-2016)	2110	100	5.3
Avg. linear increase of pub. per year (1994-2016)	5.8%	9.6%	10.3%
Top-3 source titles	Commun Soil Sci Plant Anal (3.2%) Agron J (2.8%) Plant Soil (2.4%)	Comput Electron Agric (10%) Precis Agric (5.8%) Transac ASAE (3.7%)	Agric Sys (7%) Precis Agric (7%) J Agric Econ (5%)

Only 148 (0.2%) of the 61090 fertilizers, fertilization and precision agricultural related publications address the problem of innovation adoption or diffusion in this area. The annual linear increase of publications in the fertilizer area is 5.8%. For publications concerning innovation adoption and diffusion, this increase is notable higher (9.6%); for publications regarding innovation adoption and diffusion in the fertilizer area, it is even 10.3% (Table 1).

Of the analyzed publications, eight reviews were found. 74% of the analyzed publications were published between 2007 and 2016, the oldest one has been published at 1993 (Figure 2). The top-3 journals in which 19% of the publications where published are: Agricultural System, Precision Agriculture and Agricultural Economics which all have a wider focus on agricultural research result and policy assessments.

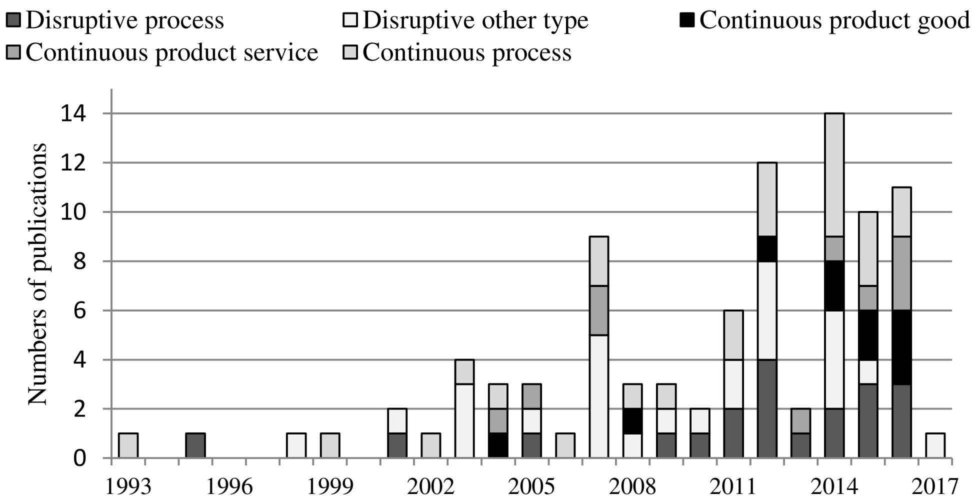

Figure 4-2 Number of publications per year and approach from 1993 till 2017.

Regarding the geographical orientation, 135 different countries where counted within the 91 publications. The share of publications focusing on agriculture in developed, developed countries (Australia, North America and Europe; n=36; 26%) is much lower than the share of publications focusing on agriculture in developing countries (Asia, Africa, Latin and Mid America; n=88; 65%). The remaining publications (n=11, 10%) have a more global orientation.

The publications were analyzed for their reference elements on the different characteristics (disruptive or continuous) and the different types (process, product, other type, according to the classification in the introduction). Most publications could be found for disruptive innovations of other types (n=26; 28%), closely followed by continuous process innovations (n=24; 26%). Twenty publications (22%) deal with disruptive process innovations. The remaining types of continuous product innovations (goods and service) are slightly smaller (n=10, 11% and n=10; 11% respectively; Table 4).

Concerning the first authors' affiliation the following research background could be detected: universities (n=54; 59%), international research institutes (n=23; 25%), national research institutes (n=7; 7%), governments (n=3; 3%), development associations (n=3; 3%), consultancy companies (n=2; 2%) and one farmer (n=1; 1%).

For our analysis of the main determines we first identified all relevant drivers within in the publications and include these in a database (**Table 4-2**).

Table 4-2 Keywords that were used to analyze the main drivers.

Theoretical approach	Keyword	
Drivers: External precursors	1. Group* 2. Network 3. Co-operation 4. Neighborhood 5. Regulation 6. Law 7. Rules 8. Observibili* 9. Visibility 10. Outcome	11. Result 12. Support 13. Help 14. Service 15. Information 16. Media 17. Communication 18. Compatibility 19. Consistency
Drivers: Factors suggested by other theories	1. Expectation 2. Concept 3. Performance 4. Imagination 5. Yield 6. Yield quality 7. Task-technol* 8. Computer 9. IT	10. EDV 11. Credit 12. Bank 13. Financ* Instit* 14. Loan 15. Market 16. Store Retailer
Drivers: Contextual factors	1. Gender 2. Age 3. Education 4. Farm size 5. Land ownership	

Afterwards, each publication was divided according to their specific eco-innovation characteristic and type (**Table 4-3** and **Table 4-4**). Each driver is than applied to the specific eco-innovation type to provide a more insight view of the most common drivers (for each innovation type) and to give more insights to the specific adoption problems.

Table 4-3 Eco-innovations in the fertilizer sector with their publication quantity and classification as disruptive or continuous and classification of the type of innovation (several publications regarding more than one innovation, publications regarding more than one type of innovation were categorized regarding their main focus).

Innovation found in the literature	Number of publications	Innovation type	
		Disruptive	Continuous
Conserve farming	11	Other type	
Diagnose tools for nutrient status	10		Product (service)
Fertigation	6		Product (good)
Fertilizers made from secondary raw materials	3		Product (good)
Intercropping with (leguminous) crops	13		Process (technological)
Knowledge training	6		Product (service)
Nanotechnology	1	Other type	

New cultivation technologies	28	Process (technological)	
Nutrient management technologies	13		Process (technological)
Precision farming	17	Other type	
Stabilized nutrients	14		Product (good)
Sustainable intensification	5	Process (technological)	

Table 4-4 Fertilizer innovation adoption publications categorized according to the main characteristic and innovation type (publications regarding more than one type of innovation were categorized regarding their main focus).

Innovation type		**Publications**
Disruptive	Process	Adesina and Baidu-Forson, 1995; Doss and Morris, 2001; Chianu and Tsuji, 2005; Oduol and Tsuji, 2005; Oladoja et al., 2009; Sirrine et al., 2010; Giller et al., 2011; Katungi et al., 2011; Akudugu et al., 2012; Kopainsky et al., 2012; Loyce et al., 2012; Mapila et al., 2012; Shiferaw et al., 2013; Ndiritu et al., 2014; Tey et al., 2014; Emerick et al., 2016; Mahadevan and Asufu-Adjeye, 2015; Manda et al., 2015; Stuart et al., 2015; Handschuch and Wollni, 2016; Ju et al., 2016; Roxburgh et al., 2016
	Other type	Stricklander et al., 1998; Swinton and Lowenberg-Deborer , 2001; Batte and Arnold, 2003; Daberkow and McBride, 2003; Marra et al., 2003; Adrian et al., 2005; Jochinke et al., 2007; Knowler and Bradshaw, 2007; Namara et al., 2007; Ogbonna et al., 2007; Takăcs-György, 2007; Gowing and Palmer, 2008; Reichardt et al.; 2009; Rezaei-Moghaddam and Salehi, 2010; Dalton et al., 2011; Kutter et al., 2011; Aubert et al., 2012; Chauhan et al., 2012; Nikkilä et al., 2012; Tey and Brindal, 2012; Busse et al., 2014; Davidson et al., 2014; Nhamo et al., 2014; Watcharaanantapong et al., 2014; Handford et al., 2015; Eastwood et al., 2017
Continuous	Process	Smale and Heise, 1993; Pandey, 1999; Haneklaus et al., 2002; Mudhara et al., 2003; Mafongoya et al., 2006; Ajayi et al., 2007; Ajayi, 2007; Akinnifesi et al., 2008; Lamba, 2009; Ajayi et al., 2011; Chen and Shively, 2011; Kanellolpoulos et al., 2012; Robertsen et al., 2012; Siddique et al., 2012; Simpson et al., 2013; Kamau et al., 2014; Simpson et al., 2014; Wainaina et al., 2014; Weber and McCann, 2014; Lamers et al., 2015a; Lamers et al., 2015b; Wossen et al., 2015; Magrini et al., 2016; Russo et al., 2016
	Product (Good)	Asfaw and Admassie, 2004; Alene et al., 2008; Khumairoh et al., 2012; Lambrecht et al., 2014; Nin-Pratt and McBride, 2014; Chang and Tsai, 2015; Ciceri et al., 2015; Hasler et al., 2016; Herrera et al., 2016; Sheahan et al., 2016

Product (Service)	Rerkasem, 2005; Hayman et al., 2007; Schreinemachers et al., 2007; Chianu et al., 2012; Moreau et al., 2013; Van Rees et al.; 2014; Huang et al., 2015; Abate et al., 2016; Zhang et al., 2016; Zhao et al., 2016

In the following, the main drivers for the different types of innovations are shortly outlined. Because of the wide range of the publications in geographic and agriculture surrounds, it was assumed that at least 25% of all publications need to mention a driver to be relevant.

Drivers for disruptive process innovations

The involvement in groups, co-operations or in advisory council could stimulate the consideration of disruptive process innovations (Mapila et al., 2012; Shiferaw et al., 2013; Ndiritu et al., 2014; Tey et al., 2014; Manda et al., 2015; Handschuch and Wollni, 2016). Furthermore it can provide a good information exchange, which is also an important trigger for the adoption of disruptive process innovations (Giller et al., 2011; Kopainsky et al., 2012; Mapila et al., 2012; Shiferaw et al., 2013; Tey et al., 2014; Manda et al., 2015; Ju et al., 2016). To push a new production technology, farmers need to have access to a market where they can buy the technology or the knowledge about this specific technology and where they can get a credit for this particular purchase. Therefore, access to credit (Oladoja et al., 2009; Katungi et al., 2011; Akudugu et al., 2012; Shiferaw et al., 2013; Ndiritu et al., 2014; Tey et al., 2014; Emerick et al., 2015; Mahadevan and Asufu-Adjeye, 2015) and a market access (Doss and Morris, 2001; Katungi et al., 2011; Mapila et al., 2012; Shiferaw et al., 2013; Ndiritu et al., 2014; Mahadevan and Asufu-Adjeye, 2015; Manda et al., 2015) are important. Disruptive process innovation seems to be sooner adopted by male farmers than by female ones (Doss and Morris, 2001; Oladoja et al., 2009; Akudugu et al., 2012; Mapila et al., 2012; Ndiritu et al., 2014; Tey et al., 2014; Manda et al., 2015; Handschuch and Wollni, 2016). One reason could be the higher risk tolerance of male people (Handschuch and Wollni, 2016). Age is seen by many publications as positive influencing factor where a younger age positively influences the innovation adoption (Adesina and Baidu-Forson, 1995; Doss and Morris, 2001; Katungi et al., 2011; Akudugu et al., 2012; Ndiritu et al., 2014; Tey et al., 2014; Mahadevan and Asufu-Adjeye, 2015; Manda et al., 2015; Handschuch and Wollni, 2016). Younger farmers have longer planning horizons and therefore have a bigger stimulus to consider new equipment investments or a change management practices than older farmers. Nearly all publications mentioned the importance of education (Doss and Morris, 2001; Oladoja et al., 2009; Giller et al., 2011Katungi et al., 2011; Akudugu et al., 2012; Shiferaw et al., 2013; Tey et al., 2014; Manda et al., 2015; Manda et al., 2015; Mahadevan and Asufu-Adjeye, 2015; Handschuch and Wollni, 2016). Higher education levels can have a stimulation effect because they can provide the farmer with a higher willingness for live long learning and cooperation. A bigger farm size can give farmers a better foundation for finical investments and can therefore trigger the eco-innovation adoption (Adesina and Baidu-Forson, 1995; Doss and Morris, 2001; Oduol and Tsuji, 2005; Akudugu et al., 2012; Shiferaw et al., 2013; Ndiritu et al., 2014; Tey et al., 2014; Mahadevan and Asufu-Adjeye, 2015; Manda et al., 2015; Handschuch and Wollni, 2016; Ju et al., 2016). If the land is additionally owned by the farmers themselves, the willingness to invest in new technologies to maintain soil fertility and soil quality is much higher (Oduol and Tsuji, 2005; Katungi et al., 2011; Mapila et al., 2012; Kamau et al., 2014; Emerick et al., 2015; Mahadevan and Asufu-Adjeye, 2015; Manda et al., 2015).

Drivers for disruptive innovations of other types

One major variable mentioned as important by almost all publication is the quality of support (Batte and Arnold, 2003; Daberkow and McBride, 2003; Davidson et al., 2014; Jochinke et al., 2007; Namara et al., 2007; Ogbonna et al., 2007; Reichardt et al., 2009; Kutter et al., 2011; Aubert et al., 2012; Nikkilä et al., 2012; Robertson et al., 2012; Busse et al., 2014; Watcharaanantapong et al., 2014; Handford et al., 2015; Eastwood et al., 2017). Reichardt et al. (2009) declared that farmers need more information about the different farming tools and more training opportunities as well as a better advisory service. Watcharaanantapong et al. (2014) even observed that farmers who obtained farming information from farm dealers, crop consultants, university extension, other farmers, trade shows, the internet, and/or news media were more likely to adopt complex disruptive innovations. Information can be seen as important precursor for innovation adoption. That goes in line with many publications for this particular type of innovation (Daberkow and McBride, 2003; Jochinke et al., 2007; Knowler and Bradshaw, 2007; Namara et al., 2007; Obonna et al., 2007; Reichardt et al., 2009; Kutter et al., 2011; Nikkilä et al., 2012; Aubert et al., 2012; Busse et al., 2014; Davidson et al., 2014; Watcharaanantapong et al., 2014; Handford et al., 2015; Eastwood et al., 2017). One source of information could be agricultural events such as field days, exhibitions and trade fairs, seminars or workshops (Kutter et al., 2011). More publications can be found for the variable expectations Batte and Arnold (2003), Marra et al. (2003), Adrian et al. (2005), Aubert et al. (2012), Tey and Brindal (2012), Busse et al. (2014) and Handford et al. (2015) all declare that farmers with high expectations are more willing to adopted new technologies. Disruptive innovations of other types are mostly orbiting around conserve or precision farming practices. These kinds of innovations are mostly technologies with a specific focus on new computer based technologies (e.g. variable fertilizer application or IT farm management systems) which require a minimum comprehension of these technologies. Therefore, most publications see the technology task fit as an important driver for the adoption (Stricklander et al., 1998; Batte and Arnold, 2003; Daberkow and McBride, 2003; Adrian et al., 2005; Jochinke et al., 2007; Knolwer and Bradshaw, 2007; Reichardt et al., 2009; Rezaei-Moghaddam and Salehi, 2010; Aubert et al. 2012; Robertson et al., 2012; Tey and Brindal, 2012; Watcharaanantapong et al., 2014; Busse et al. 2014; Eastwood et al., 2017). A higher education level seems to stimulate the adoption of new technologies (Swinton and Lowenberg-Deborer, 2001; Adrian et al., 2005; Knowler and Bradshaw, 2007; Ogbonna et al., 2007; Kutter et al., 2011; Reichardt et al., 2009; Aubert et al., 2012; Tey and Brindal, 2012; Busse et al., 2014; Watcharaanantapong et al., 2014). Davidson et al. (2014) particularly mentioned the importance of education for private sector retailers and crop advisors on the most up to date nutrient management practices through professional certification programs because these persons play a dominate role in knowledge diffusion. Because of the investment costs of these technologies, farm size can be seen as important variable, while larger farms sooner reach the break-even point of the investments (Daberkow and McBride, 2003; Marra et al., 2003; Adrian et al., 2005; Knolwer and Bradshaw, 2007; Namara et al., 2007; Takăcs-György, 2007; Reichardt et al., 2009; Kutter et al., 2011; Aubert et al., 2012; Chauhan et al., 2012; Robertson et al., 2012; Tey and Brindal, 2012; van Rees et al., 2014; Watcharaanantapong et al., 2014).

Drivers for continuous process innovations

Continuous process innovations are pushed by nearly the same drivers as disruptive process innovations. Only gender, age and education seem not as relevant as for disruptive process innovations. Therefore, the involvement in external groups (Ajayi, 2007; Lamba, 2009; Robertson et al., 2012; Wainaina et al., 2014; Stuart et al., 2015; Wossen et al., 2015; Magrini et al., 2016), the quality of support (Mafongoya et al., 2006; Ajayi et al., 2007; Lamba, 2009; Ajayi et al., 2011; Robertsen et al., 2012; Weber and McCann, 2014; Magrini et al., 2016), the information access (Smale and Heise, 1993;Pandey, 1999; Mafongoya et al., 2006; Ajayi et al., 2007; Lamba, 2009; Robertson et al., 2012; Siddique et al., 2012; Kaumau et al., 2014; Wainaina et al., 2014; Weber and McCann, 2014; Stuart et al., 2015; Magrini et al., 2016), access to credit (Smale and Heise, 1993; Pandey, 1999; Ajayi, 2007, Ajayi et al., 2011; Wainaina et al., 2014; Lamers et al., 2015a; Wossen et a., 2015) and market (Pandey, 1999; Ajayi, 2007; Ajayi et al., 2007; Simpson et al., 2013; Kamau et al., 2014; Simpson et al., 2014; Wainaina et al., 2014; Stuart et al., 2015; Magrini et al., 2016) and the farm size (Smale and Heise, 1993; Mudhara et al., 2003; Robertsen et al., 2012; Kamau et al., 2014; Wainaina et al., 2014; Weber and McCann, 2014; Wossen et al., 215) are most important.

Drivers for continuous product innovations (goods)

To evaluate the purchase of a new product, the user needs to be informed about the possibility to buy a new product and the improvements of this new product. Therefore, information is mandatory (Lambrecht et al., 2014; Chang and Tsai, 2015; Hasler et al., 2016; Herrera et al., 2016). That goes in line with the quality of support. Here a good support or consulting could stimulate the farmers to try a new product (Chian et al., 2012, Lambrecht et al., 2014; Hasler et al., 2016; Herrera et al., 2016). New products are in need for a purchase opportunity by farmers. Hence the access to a market selling the new products is necessary. If the farm surrounding does not provide any opportunity to by an innovative product, the farmers are less aware and have no opportunity to come in contact with these new products (Alene et al., 2008; Chian et al., 2012; Lambrecht et al., 2014; Pratt and McBride, 2014; Ciceri et al., 2015; Sheahan et al., 2016). If a new product implies further investments, the access to credit can motivate the innovation adoption (Asfaw and Ademassie, 2004: Chianu and Tsujii, 2005; Alene et al., 2008; Lambrecht et al., 2014). Age and education level can also stimulate the adoption by having a longer planning horizon and a better formal training (Asfaw and Ademassie, 2004; Chianu and Tsujii, 2005; Alene et al., 2008; Lambrecht et al., 2014; Sheahan et al., 2016).

Drivers for continuous product innovations (service)

The involvement in co-operations or consultant groups can stimulate the adoption of service innovations because these groups can offer this kind of service or can establish contacts (Schreinemachers et al., 2007; Huang et al., 2015; Abate et al., 2016). When farmers exploit services, they want to see the results in higher yields or input effort. Therefore, the observability of this services are important for the continued use (Haymann et al., 2007; Schreinemachers et al., 2007; Chianu et al., 2012; Zhang et al., 2016). The same holds true for the quality of the support. By providing a specific service, a continuous support is necessary (Haymann et al., 2007; Huang et al., 2015; Zhang et al., 2016). Here a fluent information flow, which is also important for the innovation adoption, is also ensured (Hayman et al., 2007; Chianu et al., 2012; Moreau et al., 2013; Zhao et al., 2016). For product innovations offering new ways of services, also gender (male; Schreinemachers et al., 2007; Chianu et al., 2012; Abate et al., 2016), age (Schreinemachers et al., 2007; Abate et al., 2016; Zhang et al., 2016) and farm size (Schreinemachers et al., 2007; van Rees et al., 2014; Zhang et al., 2016) can trigger a further adoption.

4.4 Discussion and conclusions

This review shows that the largest group of publications focuses on farm level analysis. The structural analysis of multi-level interactions, which can play an important role for the innovation adoption, is rarely part of the analytical framework of the considered publications. Only few studies even mentioned level of higher dimension (e.g. national policies; (Ajayi et al., 2007; Huang et al., 2015)). The observed literature clearly displays that the relationship in innovation creation and adoption between farmers and researchers is remained to be the same, with the researcher as innovation developers and farmers as innovation adopters. In the majority of the publications, the farmers have no or little influence on the innovation itself. In some studies, the (national) agricultural research and extension system have a massive impact on promoting the innovation adoption (Jochinke et al., 2007; Loyce et al., 2012). That leads to the conclusion, that within the fertilizer or agricultural sector, more individual decisions and therefore more individual drivers play important roles for the eco-innovation adoption and diffusion. Comparing it to other publications dealing with main drivers of eco-innovation adoption, the regulatory pressure, market demand, competitive pressure or stakeholder pressure seems to play a minor role (Díaz-García et al., 2015; Bossle et al., 2016; del Río et al., 2016; Hojnik and Ruzzier, 2016). That even makes the implementation of specially suited to ecosystems and eco-innovation much more difficult (Tsvetkova and Gustafsson, 2012; Hellström et al., 2015). The fertilizer sector showed a clear focus on more individual determinates, like task technology fit, age, education or gender (**Table 4-5**). Therefore we assume that a model describing more individual determinates of innovation adoption, like the TAM, is more suitable for explaining the low adoption of eco-innovations within the fertilizers sector, than classic business or economic models.

Table 4-5 Drivers for different innovation types mentioned by at least 25% of all publications

Drivers	Disruptive process innovations	Disruptive innovations other type	Continuous process innovations	Continuous product innovations (goods)	Continuous product innovations (service)
Number of publications mentioning this driver as important					
External precursors					
Involvement in external groups' or co-operations	6		7		3
Regulation					
Observability					4
Quality of support		14	7	4	3
Information	7	13	10	4	4
Compatibility					
Factors suggested by other theories					
Expectation		7			
Task-technology fit		14			
Access to credit	8		7	4	
Market access	7		9	4	
Contextual factors					
Gender	8				3
Age	9				3
Education	10	10		5	
Farm size	10	11	7		3
Land owner-ship	5				

An additional a distraction of the publications into diverse agricultural areas could be useful. For example many continuous process innovations (like nutrient management technologies) are already used in higher amounts in developed countries. By splitting the research up to more specific agricultural areas more precis predictions about the eco-innovation adoption would be possible. The literature review done in this paper generally showed, that more individual factors are more important for the innovation adoption on farm level, than economic explanation putting the farm as firm into the focus. Additionally the characteristic of a specific innovation can lead to different solutions supporting the adoption. Disruptive process innovations are driven by information, education, age and farm size. That leads to the conclusion, that this type of innovation requires a more radical rethinking in the farm management and production systems, making the adoption more reasonable for bigger farms with a longer planning horizon. Disruptive eco-innovations of other types are mostly pushed by factors regarding the knowledge and education of the single farmer, like the education level, the task technology fit, information and support. Here targeted training opportunities for farmers to enhance their skill and knowledge so that they can cope with the complexities of the systems can help to overcome adoption problems. The adoption of continuous innovation is mostly motivated by the driver information. Here a more training opportunities and consulting could actively simulate a positive adoption.

More research is general needed to compare developed countries and developing countries. Some of eth innovations classified as continuous innovations could be disruptive in developing countries because of a lack of market, trading opportunities or training. Additionally it would be interesting what happened to the individual adoption decision, if the characteristic of an innovation change form disruptive to continuous (for example the use of apps to characterize the nutrient status of a plant). Here more and better adjusted research is absolutely necessary to can to more precise prediction about the innovation adoption in the field of fertilizer and agricultural eco-innovations.

5. What they know: Drivers for the adoption of eco-innovations in the German fertilizer supply chain

Chapter 4 answers the research question 4:

How do different actors of the fertilizer supply chain perceived the necessity and knowledge of eco-innovations?

5.1 Introduction

Along with the projected global population increase to more than 9 billion in 2050 the demand for food is growing rapidly (United Nations, 2015). Up to now, food production kept up with population growth through the use of new agricultural techniques, including plant breeding, plant protection, cultivation techniques, use of irrigation and fertilization. However, at the same time as these changes in agricultural productivity occurred, consumer behavior concerning food and the political economy of farming also changed (Goodman and Watts, 1997; Smith et al., 2008). Agricultural systems are nowadays increasingly recognized as a significant source of environmental damage (Pretty and Hine, 2001; Tilman et al., 2002; Pretty, 2008).

Nearly 50% of the increase of agricultural output, especially in cereal production, is based on fertilizer use (FAO, 2012). Fertilizers help to maintain soil fertility and productivity through supplying essential plant nutrients. Fertilizers also show negative externalities, especially the emission of greenhouse gases during the production process as well as during and after field

This chapter is based on following publication: Hasler, K., Omta, S.W.F., Olfs, H.-W. and Bröring, S. (2016). Drivers for the adoption of eco-innovations in the German fertilizer supply chain. *Sustainability*, 8, 682.

application (Jenssen and Kongshaug, 2003; Wood and Cowie, 2004). Overall 12% of the greenhouse gas emissions worldwide are related to agriculture (Smith et al., 2007) with 38% stemming from the use of organic and mineral fertilizers alone (Wegner and Theuvsen, 2010). Additionally, nutrient leaching to ground and surface waters are resulting in eutrophication of aquatic ecosystems with increased growth of algae and finally decreasing the levels of oxygen (FAO, 2012). Also the decline of non-renewable resources (e.g. phosphorus or potassium; (EFMA, 2000f) is connected to the use of mineral fertilizers.

Today, concerns about sustainability focus on the need to develop agricultural technologies and practices that (1) do not have negative effects on the environment, (2) are available to and effective for farmers, and (3) lead to both improvements in food productivity and have positive side effects on environmental goods and services (Pretty, 2008). To meet the challenges of the global food security in a sustainable way requires the intensification of knowledge-based approaches and the use of modern agricultural practices (Spiertz, 2010), which can be classified as eco-innovative. More precisely, eco-innovations are defined as innovations that reduce the environmental impact or the use of natural resources (Kemp et al., 1998; Rennings, 2000; Ekins, 2010) leading to a more responsible application of fertilizers in order to achieve low input/high output farming systems. Kemp and Pearson (2008) defined eco-innovation as " *(...) the production, application or exploring of a good (...) that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resource use (including energy use) compared to relevant alternatives*" (p. 11). Ekins (2010) even went one step further and defined eco-innovations as "*…a change in economic activities that improves both the economic and the environmental performance of society*" (p. 269). In the present study we focus on eco-innovations in the field of fertilizers that exist already for some time, but that are not yet well adopted by farmers and other actors in the fertilizer supply chain. Due to this fact, we draw upon the reasoning of Carruthers and Vanclay (2012) who stated that "*…even though an idea or a technology may have been in use for some time, it is the novelty of the concept to the new user that is critical in understanding something as innovative.*"

One focus of this study is to explore the reasons for the limited innovation adoption reflected by missing drivers and the lack of knowledge sharing between the different actors in the fertilizer supply chain. Numerous studies have shown, that only a combination of innovation system thinking and a proper knowledge sharing leads to a higher level of adoption of new or improved technologies or practices (Martino and Polinori, 2011; Amankwah et al., 2012; Tepic et al., 2012; Totin et al., 2012; Aguilar-Gallegos et al., 2015). An innovation system in this context is the combination of different factors – economic, social, political, organizational, institutional – that influence the development, diffusion and adoption of innovations (Edquist, 2005). An innovation system can be defined as the set of all individual and organizational actors that are relevant to innovation in a particular sector (Lundvall, 1992; Malerba, 2002; Anandajayasekeram and Gebremedhin, 2009; Amankwah et al., 2012). For innovation in supply chains this approach highlights the importance of information exchange across multiple links in the chain, which is enabled by partnerships between upstream and downstream actors

(Mylan et al., 2015). As a result these innovation networks have become more and more complex due to the development of agriculture (diversification or specialization of producers and products (Klerkx et al., 2010).

Aguilar-Gallegos et al. (2015) conclude that the structure of agricultural networks leads to different rates of innovation adoption. Studies in the management literature (Cohen and Levinthal, 1990; Keskin, 2006; Lund Vinding, 2006) and the agricultural economics (Tepic et al., 2012; van Rijn et al., 2012; Gellynck et al., 2015) also examined adoption as a function of learning orientation. Different parts of production systems and of the environment in which they are embedded (e.g., the value chain, the market, the policy environment) need to develop simultaneously in order to enable innovation. This requires interactions amongst multiple actors to acquire and assimilate new knowledge (Geels and Schot, 2007; Amankwah et al., 2012). As the broad majority of agricultural innovations are developed outside the farm, the development of the absorptive capacity highly depends on more than internally directed and funded innovative activities, both inside and outside the agricultural production systems (Cohen and Levinthal, 1990; Jansen et al., 2005; Martino and Polinori, 2011). Although widespread services and agricultural consultation have become increasingly common in the diffusion of information for agricultural technology, the awareness of the applicability of many agricultural technologies and practices may still not be homogeneous (Dinar et al., 2007; Klerkx et al., 2010).

Existing research has shown that a firm´s decision to introduce eco-innovations is influenced by a variety of factors, including regulation (as the “regulatory push/pull effect”), technology push, market pull (e.g. the concept of customer benefits), policy (changing laws) and firm specific aspects (such as knowledge transfer mechanisms and involvement in networks [Davis, 1989; Rogers, 2003; Frondel et al., 2008; Horbach, 2008; Horbach et al., 2012; Dolinska and d´Aquino, 2016]). Based on these studies we consider the following three drivers as highly relevant for the adoption of eco-innovations: (1) market pull (measured by “perceived need for action”); (2) regulation (measured by “regulation awareness”) and (3) firm specific aspects (measured by “knowledge on eco-innovation” and “markets pull” or “technology push”). We strive to explore to what extent these three drives differ among the three aforementioned supply chain actors. To this end, by focusing on the adoption of innovations from a supply chain perspective, the paper at hand seeks to contribute to the emerging literature on eco-innovations. So far, to our best knowledge, this is the first paper looking at eco-innovation adoption and diffusion of knowledge using a supply chain perspective. Additionally, we were able to show that not only users of eco-innovations (farmers) are blocking the diffusion process but also the traders or/and producers of fertilizers. We aim to provide recommendations to improve knowledge sharing and collaboration within agricultural supply chains to stimulate the development and implementation of eco-innovations.

5.1.1 Theoretical framework

We draw upon the following definition of eco-innovation: “The production, application or exploring of a good (…) that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resource use” (Enkins, 2010). Further an eco-innovation must have a benefit linked to both the environmental impact of a product or service and to the economic performance (Rennings, 2000). Additionally to the definitions of Kemp and Pearson (2008) and Ekins (2010) it does not matter if environmental improvements have been the declared goal or came along as by-product or simply by chance. That means that eco-innovations can be the result of other economic decisions such as reducing costs and not have been predominantly motivated by environmental concerns (Horbach, 2012).

In line with our overall research goal (i.e. understanding the drivers for the adoption of eco-innovations) we strive to explore (1) if innovations are pulled by farmers or pushed by other actors within the fertilizer supply chain, (2) the perceived need for action to mitigate climate change, (3) the regulation awareness and (4) the knowledge on eco-innovations among different fertilizer supply chain actors.

Technology push or market pull

Generally speaking, an innovation process can either be initiated upstream through the enhanced involvement of farmers in innovation development planning (market pull [Heemskerk, 2005]) or downstream “pushed” from innovative fertilizer producers (technology push [Morgan and Murdoch, 2000]). Most farms in Germany are family based with minor changes over the years and most famers tend to think about their work pretty much as they always have done. Sivertsson and Tell (2015) claimed that the request for innovation is closely linked to the human capital on farms, leading in many cases to the so called “locked-in syndrome” where no further changes are taken into account. Additionally, most environmental problems represent negative externalities of food production, such as emissions to the atmosphere, so that for many farmers there is no clear economic stimulus to adopt eco-innovations as long as the end-consumer do not want to pay extra for such products (Rehfeld et al., 2007). Thus, we strive to understand, if the innovation system in the fertilizer supply chain is more pushed by producers or pulled by farmers.

Perceived need for action to mitigate climate change

In a very early state of innovation adoption stands the awareness of the problem or opportunity. In this context awareness means not just knowing that an innovation exists, but that it is potentially of practical relevance to the user (Pannell, 1999). Awareness and relevance can be linked to the so called “perceived need for action” (Rogers, 2003). As long as the farming system and the agricultural environment do not modify significantly, the perceived need for action at the farmers level should be very low. However, within predicted changes due to climate change in Germany there could be some considerable effects on plant yields and fertilization periods (like modified rainfall, changes in total seasonal precipitation or in its pattern of variability and extreme weather scenarios, such as spells of high temperatures or droughts [Olesen and Bindi, 2002]). Furthermore the continuing environmental discussion, influenced by information coming from customers, suppliers, competitors or consultants, conferences and exhibitions, universities and other public research institutions or (scientific) journals could create a higher awareness of the perceived need for action (Rogers, 2003; Horbach et al., 2012). That could lead to the conclusion, that eco-innovations are seen as possible solutions for the upcoming problems.

Here we seek to explore if the fertilizer supply chain position and the perceived necessity to adopt eco-innovation differ through the supply chain by detecting how the different fertilizer supply chain actors comprehend the changes in fertilization patterns due to climate change.

Regulation awareness and knowledge on eco-innovations

Klein Woolthuis et al. (2005) reviewed the commonly occurring types of innovation system failure and designed a framework for structured analysis of constraints in innovation processes. The innovation system framework consists of a matrix of system elements: barriers that may block learning and innovation and the actors who reproduce the barriers (Klein Woolthuis et al., 2005; van Mierlo et al., 2010). Our research design classified the following two barriers:

- Institutional failure being failures in the framework of regulation and the general legal system (Smith, 2000).
- Network failures (Carlsson and Jacobsson, 1997) i.e. the ‘blindness’ that evolves if actors have close links to each other and as a result miss out on new outside developments.

Regulatory instruments include all political interventions that formally influence social and economic action through binding regulations (Krott, 2005). They suggest norms, rules and acceptable behaviors while limiting certain activities in a society (Lemaire, 1998). Encouraging soft environmental measures (e.g. guidelines or memorandums) by governments, such as environmental accounting systems, eco-labels or eco-auditions may improve the information base for eco-innovations (Jang et al., 2015). The analysis of institutional barriers in this article builds upon the problems which would arise with the amendment of the German fertilizer ordinance. Environmental regulatory instruments and environmental policy instruments (especially soft regulations) are highly relevant drivers for the adoption of eco-innovations (Cleff and Rennings, 2000; Rehfeld et al., 2007; Horbach 2008). Therefore we included environmental policy and restrictions as a second important determinant for the adoption of eco-innovations in our study, also known as the “regulatory push/pull effect” (Green et al., 1994; Rennings, 2000; Brunnermeier and Cohen, 2003). Regulation is not always seen as an undesirable cost-increasing factor but also as an activator for innovativeness that could lead to a first-mover advantage (Lieberman and Montgomery, 1988). As a result the impact of regulation as a driver for eco-innovations might differ depending on how actors deal with regulatory changes, taking a pro- or reactive approach (Demirel and Kesidou, 2011). We utilize the possible reduction of nitrogen and phosphorus use (extracted from the expert interviews as a potential solution) as precursor for presumable eco-innovations in fertilization. In a further step we asked all members of the supply chain to what extent they presume further restriction. We assumed that more critical answers lead to a higher possibility for the consideration of eco-innovations. Thus, we strive to explore the different perception of regulatory change as a driver for eco-innovations in how the different actors of the fertilizer supply chain anticipate changes in regulation.

The analysis of the network failures is based on the assumption, that agricultural supply chains in general and the German fertilizer supply chain in particular are very closely linked with trusted and long-lasting relationships. Additionally we assumed that farming retained many of its traditional characteristics (large number of small producers, family based enterprises, etc.), but more and more fertilizer types or technical equipment being available for agriculture production. Selecting these options became a specialized task and farmers started to rely on external consulting which might lead to an uneven distributed knowledge (Morgan and Murdoch, 2000). However, a fluent and up- and downstream flow of information is fundamental for achieving coherence among the chain actors and increasing the capabilities of the chain (e.g. Simatupang et al., 2002; Skipper et al., 2008; Kottila, 2009). The adoption of innovation is a dynamic learning process with can be broken down into stages, always starting with the awareness of the problem or opportunity (e.g. Lindner et al., 1982; Pannell, 1999; Rogers, 2003). Porter and van der Linde (1995) claimed that firms do not see the potential of eco-innovations because they are *"(...) still inexperienced in dealing creatively with environmental issues"* (Porter and Van der Linde, 1995, p 99). Environmental and economic friendly innovations are not realized because of incomplete information, organizational and/or coordination problems (Porter and Van der Linde, 1995) and firms are not able to recognize the cost saving potentials of eco-innovation. Additionally, Garbade et al. (2013) concluded that knowledge enhancement also offers the possibility for bridging the gap between exploration and exploitation of research results. In the present study our focus lays on the knowledge transfer mechanism. Therefore, we explore the knowledge distribution along the fertilizer supply chain in the following research question: Does the level of knowledge on eco-innovations differ among the actors in the fertilizer supply chain?

5.1.2 The fertilizer supply chain and its existing eco-innovations

The fertilizer supply chain in Germany

Although there exist a diversity of supply chain structures, we conceptualize the fertilizer supply chain as consisting of three main steps: producers, traders and farmers consuming the fertilizer in their arable crop farming practices. Due to high market entry barriers such as capital and energy costs only nine fertilizer producers are still operating in Germany at present (one plant for fertilizer production containing mainly phosphorus, one large company for potassium based fertilizers and seven production plants for nitrogen, multiple nutrient fertilizers or special fertilizers (IVA, 2014).

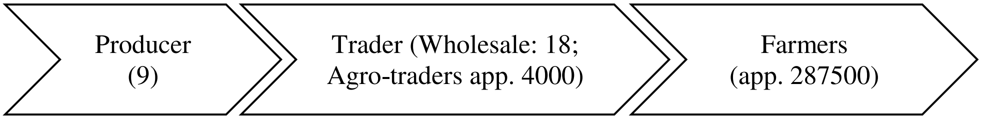

Figure 5-1 German fertilizer supply chain - number of supply chain partners in brackets (IVA, 2014).

In most areas in Germany fertilizer (as well as other agricultural products) are traded in a two-step supply chain starting at wholesale which sell to several smaller local agro-traders (compare Fig. 1). In 2000 still 18 wholesalers were operating in Germany with a tendency for further structural change (IVA, 2014). Thus, the second step of the fertilizer supply chain mainly consists of agro traders. These traders are not only selling fertilizer, but also other agricultural input factors (e.g. seeds or pesticides). In most cases they even purchase the entire harvest from arable farmers and are offering facilities for storage and logistics. In the year 2000 there were approximately 4000 agro-traders operating as single trading companies or in larger cooperatives (IVA, 2014), but in the last couple of years this number is constantly decreasing. At present app. 287500 farmers are operating in Germany (Statistisches Bundesamt, 2013; **Figure 5-1**).

Eco-innovations in the fertilizer supply chain

Information on eco-innovations in the German fertilizer sector was gathered through expert interviews and analyses of secondary data (spring 2013). In the last decade a high number of eco-innovations were generated changing fertilizer application techniques and fertilizer properties (Renni and Heffer, 2010). However, many of them are only useful in extreme cultivation areas (e.g. genetically modified plants (GMOs) with a higher tolerance to salinity or drought), others are made for specific agricultural practices (e.g. special urea coatings for rice production [Renni and Heffer, 2010]) Recently developed eco-innovation in the German fertilizer related area are: GMOs, strip till, in-field variable fertilization (precision farming), foliar fertilization, stabilized nitrogen fertilizer (SNF), fertigation (FG) and secondary raw material fertilizers (SRMF) and fermentation residues from biogas production. We excluded most of these eco-innovations from our research due to the following reasons: the use of GMOs is highly controversial discussed in the German society and between consumers (Lusk et al., 2003), till, foliar fertilization and area specific fertilization will change the application technique and therefore the agriculture system and fermentation residues from biogas production are too closely linked to the original organic fertilization. Finally, we arrived at three specific fertilizer eco-innovations with a high relevance for the fertilizer sector (SNF, FG and SRMF). Additionally all experts during the interviews mentioned all three of them (together with GMO and improved organic fertilization) as relevant in association with legal and environmental changes within the German agriculture surroundings. All three innovations are only incremental and don’t change the whole fertilization system. Furthermore we decided to get deeper insights into these eco-innovations, because they might alleviate the problems associated with climate change in Germany. Due to the expected increase of temperatures, more humid winters and more frequent extreme weather events (Schönthaler et al., 2015), it could become necessary to modify the nitrogen fertilizer product to avoid undesirable losses to the environment. Additionally, an increasing number of drought periods in some areas of Germany (Schönthaler et al., 2015) could lead to an increase use of irrigation systems. In association with the amendment of the German fertilizer ordinance, it could become even more important to close nutrient cycles and to use existing raw materials as fertilizers.

In the following we briefly explain their (1) underlying technological principle, their (2) specific eco-innovation potential and (3) their current status of market adoption.

Stabilized nitrogen fertilizers

1) SNF, first introduced in the 1950ies can be formulated in three different ways. The first is to add a coating to the granular which allows for a controlled release of the nitrogen. The second way is to supply nitrogen in a less soluble from that needs to be converted chemically or biologically to a more soluble and plant available from (sometimes also called "delayed release"). The third way is to add an inhibiting chemical that blocks or at least delays the transformation of urea/ammonium nitrogen into nitrate nitrogen (Watson and Laughlin, 2010).
2) SNFs have been shown to reduce N leaching (Hanafi et al., 2002) and gaseous emissions leading to increased nitrogen use efficiency. Hence, they present an important eco-innovation, since the use of nitrogen fertilizer at field level is a primary source of CO_2 and N_2O emissions (Bellarby et al., 2008; Bentrup and Pallière, 2008).
3) It has been estimated that stabilized N fertilizers comprise only 8-10% of the fertilizers used in Europe (Lammel, 2005; Shaviv, 2005), 1% in the USA and only 0.25% in the world (Hall, 2005). The market share of these products in German agriculture is still very limited. Legal requirements have led to a faster adoption rate of this technology especially in areas with high livestock intensity, while in other regions market penetration is developing rather slowly. Only about 10% of the total SNF production is used on agricultural crops (Statistisches Bundesamt, 2013), the remainder is used for non-agricultural markets (e.g. lawns, golf courses, fruit trees and vegetables [Shaviv, 2005]).

Fertigation

1) FG is defined as application of soluble fertilizer via the irrigation water (Kafkafi, 2008). This technology was initially developed in the 1970ies 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 greater control over nutrient availability to the crop. When nutrients are applied shortly before they are actually needed, it is possible to reduce losses of nutrients to the environment and also to make the producers less dependent on weather conditions.

2) In Germany the need for irrigation is not so widespread compared to Mediterranean countries, but with changes in rainfall patterns due to climate change, FG might become im-

portant to enable high yields in the future. The benefits of FG are twofold: (1) a reduction of fertilizer and water needed for crop production and (2) the application of nutrients can be controlled at the precise times they are needed (Bhattarai et al., 2004; Kafkafi, 2008). However, FG also has some disadvantages like high investment costs, organic fertilizer cannot be used and a supply of high quality water resources must be guaranteed.

3) At the moment market adoption of FG in Germany is rather low. Due to its high investment costs for the irrigation infrastructure FG is only profitable for crops with high profit margins (like strawberries, tomatoes or herbs). However, experiments in regions with frequent drought stress periods with potatoes have shown promising results (Darwish et al., 2006). Assuming climate would become warmer and dryer, FG seems to be a viable option for many regions in Europe (Nunes et al., 2008).

Fertilizers made from secondary raw materials

1) SRMF are fertilizers made from so-called “secondary raw materials”, such as sewage sludge, compost or other organic substances like horn meal, crop residues or various non-usable leftovers from food production.
2) If these materials are used as fertilizers they need to comply with the German fertilizer regulation (DüMV, 2012) which, at the moment, bans the use of bone meal, meat meal, animal meal and blood based products. However, such SRMF products are expected to become especially important when non-renewable raw materials like rock-phosphate become scarce and regulations regarding the closing of nutrient cycles become mandatory. Additionally, with new filter, removing or cleaning technologies (de-Bashan and Bashan, 2004) many of the above mentioned materials could also be used as base materials for fertilizer production. This will result in a reduction of the use of non-renewable resources as source material for mineral fertilizer production.
3) Overall these materials are quite often used in German agriculture, but often there is a lack of awareness of these products reflected by the fact that most farmers are neglecting them when calculating fertilizer compositions (DüMV, 2012).

5.2 Methods

We seek to obtain information about the drivers, determined by the above mentioned factors (i.e. *technology push/market pull, perceived need for action, regulation awareness* and *knowledge*) from actors of the three levels of the supply chain operating in Germany. Therefore, we apply a mixed-method research design conducted in a two-step approach beginning with exploratory expert interviews followed by a postal questionnaire.

5.2.1 Step one: exploratory interview with experts in the fertilizer sector

Experts for the interviews (n=8) conducted in spring 2013 were two CEOs and two regional consultants of different fertilizer producers in Germany, the sales directors of two different fertilizer trading organizations and two plant nutrition professors from agricultural universities in Germany. The following topics were discussed: (1) expected future supply chain developments, (2) expected political changes, (3) expected developments of new technologies and (4) new ways of nutrient recycling. The transcribed interviews were computer-assisted encoded, in order to identify the most relevant aspects. Then, we conducted a group comparison of the different assessments of the individual supply chain actors. In a final step we summarized the statements of every supply chain level to a general opinion.

5.2.2 Step two: questionnaire with actors across the fertilizer supply chain

Based on the results of the interviews a postal questionnaire was developed as second step and sent to 250 supply chain actors in fall 2013. We selected these 250 participants for the survey from the customer lists of two agricultural trading and distribution cooperatives (Verband Deutscher Düngermischer and Raiffeisenverband) and agricultural students stemming from farms. In total 57 individuals responded (response rate 23%). Twelve of them (21% of the sample) were CEOs and regional consultants of the main fertilizer producing companies in Germany, 34 (60% of the sample) belonged to the supply chain level of agro traders and eleven farmers, representing the final level of the fertilizer supply chain (19% of the sample), responded.

5.2.3 Measurement used in the questionnaire

All questions concerning the four drivers for eco-innovations (*technology push/market pull, perceived need for action, regulation awareness* and *knowledge about eco-innovations*) were measured with seven-point Likert-scales (1=total disagree to 7=total agree). Details on *technology push/market pull* were gathered by asking the participations the following items: (1) I use new technologies ahead of my competitors and (2) new technologies have a better work performance. The *perceived need for action* was measured by the items: (1) frequency of extreme weather scenarios will increase and (2) fertilization strategies have to be adapted to extreme weather scenarios. The same approach was used for the determinant of the *regulation awareness*. Here, participants were asked to what extent they expect further restrictions concerning the use of nutrients (i.e. the use of mineral nutrients, especially nitrogen and phosphorus, will be further restricted). To explore the knowledge distribution along the supply chain, *knowledge* regarding eco-innovations was measured with a dichotomous yes/no question (Do you know SNF? Do you know what FG is? Do you know SRMF?). Three additional open questions were used to get a deeper insight in the ideas of the different respondents about the environmental challenges the fertilizer supply chain is facing and the possible solutions in the field of eco-innovation, and if they see it as a chance or a threat. Due the small sample size, we only report average answer values, i.e. means (M) together with their standard deviation (SD). Significant differences are calculated by using ANOVA followed by multiple comparison test (Tukey) and are reported as significant with p-values of ≤ 5%. We only report the p-values (P) of significant differences. Statistical differences concerning the knowledge about the three eco-innovations of the different supply chain actors (producer, trader, farmer) were evaluated by using a non-parametric multiple contrast test (Konietschke et al., 2012). All statistical tests were computed by tools of the software R (R Development Core Team, 2015).

5.3 Results

5.3.1 Technology push or market pull

During the interviews all eight experts agree, that the agricultural sector will undergo profound changes in the next decade. Here most of them mentioned an intensification of animal and/or crop production and assessed that small scale low income family based farms seems to be a discontinued model. Especially the experts working for fertilizer producers or trading organizations expect a higher global cross-linkage, for example with the US or Chinese markets. One solution nearly all experts (except the two CEOs) mentioned was that the future of agricultural businesses is based on well-educated farmers, seeing themselves as business manager. The experts working for fertilizer producers even desire a live-long-learning of all supply chain partners and more openness towards new developments.

Table 5-1 Technology push or market pull in the context of technology evaluation of the different supply chain actors within the fertilizer supply chain (average values and standard deviation).

	Supply chain position		
	Producers (n=12)	**Traders (n=34)**	**Farmers (n=11)**
First user of new technologies	4.37/1.85	4.08/1.61	3.54/1.63
New technologies are better	5.00/1.60	4.41/1.21	4.00/1.18

All items were measured with a seven-point Likert-scale (1=total disagree to 7=total agree)

In our questionnaire we were interested if the openness towards new technologies increase or decrease along the supply chain. Going down the fertilizer supply chain it seems, that farmers are the most skeptical towards new technologies (**Table 5-1**). Even if the decrease is not significant, that could mean innovations are less likely pulled by farmers but rather follow a technology push approach.

5.3.2 Perceived need for action

In the interviews all eight experts agreed that extreme weather scenarios (e.g. drought periods) might occur more often in the next couple of years. As a consequence, the period for fertilizer application might be shorter and/or the management system must be adapted to new climate conditions. Obviously the awareness of necessary changes due to climate change exists, but differs across the supply chain.

We were also interested in the question, if environmental concerns are also perceived as business opportunity by the different supply chain actors (producers, traders, farmers). The fertilizer producers indicate to reflect on environmental aspects in their businesses strategies (e.g. with labeling or proactive initiatives). Mostly they take that into their consideration because they bearing the interests of the end-consumers of agricultural goods in mind. *"The Carbon*

Footprint in marketing will come. It will take some time, but it will come. (P2)". However, they seem to be insecure to what extent these are considered during the purchasing process of farmers. Most of the experts are convinced that farmers are not buying based on any environmental motivation. According to one producer, farmers to not perceive any need to mitigate climate change: *"The whole environmental discussion is no issue for the farmer; it is more seen as harassment or political instructions. That issue has no positive meaning for farmers (P1)".* One trader is also questioning the motivation of farmers: *"Are farmers buying with environmental perspectives? I don´t think so (T2)."* However, looking at the statements of the farmers in the open question part, some of them indicated that they would buy with an environmental motivation if that would be honored and lead to a higher willingness to pay at consumer level.

Across the entire sample, in general supply chain actors agreed that extreme weather scenarios will increase and that fertilization management has to be adapted [extreme weather scenarios will be more frequent (M 5.6; SD 1.27); fertilization has to be adapted to extreme weather scenarios (M 5.72; SD 1.05)].

However, as depicted in **Table 5-2**, results differ according to the chain position. The group of fertilizer producers is very sure, that climate change will affect farming activities in general and fertilization practice in Germany. They see clear opportunities for new application techniques. Also farmers see climate change problems quite clearly. Although farmers are the ones that are directly affected, they indicate to have no idea how to manage this problem. Traders are not so sure about the statement that climate change may affect German agriculture.

Table 5-2 *Perceived need for action* in the context of climate change of the different supply chain actors within the fertilizer supply chain (average values and standard deviation; a and b indicate significant differences between the single supply chain actors at $\alpha \leq 0.05$ measured by ANOVA followed by multiple comparison tests).

	Supply chain position		
	Producers (n=12)	**Traders (n=34)**	**Farmers (n=11)**
Qualitative statement	*"Climate change in Germany will result in more dry periods and extreme weather scenarios (like tornados, extreme rainfall events or extreme frost events in winter)."*	*"What climate change?"*	*"Would buy with environmental motivation, if that would be honored or paid."*
More frequently extreme weather scenarios	6.00/1.10	4.96/1.74	5.82/0.87
Fertilization has to be adapted to weather scenarios	6.38/0.74^{a}	5.22/1.27^{b}	5.54/1.13^{ab}

All items were measured with a seven-point Likert-scales (1=total disagree to 7=total agree)

As detailed in **Table 5-2** the traders' mean values for both items of the "*perceived need for action*" category were lower than the ones of producers and farmers whereas only the item *"fertilization needs to be adapted to extreme weather scenarios"* differs significantly from producers and traders [P 0.045]). Obviously concerns about climate change or global warming are seen as less critical by traders than by producer and farmers. Some of the traders even negate climate change at all in the open question part.

5.3.3 Regulation awareness

Most experts in the interviews agree that legal regulations linked to the program "CAP 2020" (European Union, 2016) will increase with the main concept of changing the agricultural subsidies from direct payments per hectare to targeted environmental programs. Furthermore most of them are aware of these changes, but the consequences are assessed in very different ways. Producers are quite sure, that in addition to the political changes the public pressure will force farmers *"...to include ecological aspects to their decisions like nature protection, animal welfare or environmental consideration (P3)."* Producers even expect political changes based on societal pressure and new social values. Traders agree that more regulatory constrains will occur, but they have little ideas on scope and content of these changes.

Based on our questionnaire it seems that producers, traders and farmers are aware of regulation as a driver for eco-innovation. In the qualitative statements we find that especially producers try to anticipate these to find solution for regulatory compliance. However, going downstream the supply chain we can observe that traders and farmers seem to be less pro-active and show a mere "wait and see" attitude to regulation. Traders and farmers perceive regulations as a given force that cannot be influenced or changed as indicated by the statement *"we have no choice"*. Farmers just admitted that they have to possibly react and deal with new situations (**Table 5-3**). Especially the farmers expect a further restriction of the use of nitrogen and phosphorous (M 5.18; SD 0.87). However, even though the means of the supply chain actors differ, no significant differences could be detected.

Table 5-3 *Regulation awareness* of the different supply chain actors within the fertilizer supply chain (average values and standard deviation).

	Supply chain position		
	Producers (n=12)	**Traders (n=34)**	**Farmers (n=11)**
Qualitative statement	*"The nutrient surplus will be further regulated (finally to achieve a balanced input/output nutrient ratio) by the European government, because existing regulations have not lowered the nitrate emissions to ground water bodies."*	*"...cannot be influenced or changed."*	*"We have no choice!"*
Further restriction of N and P* use	4.58/1.68	4.73/1.42	5.18/0.87

All items were measured with a seven-point Likert-scales (1=total disagree to 7=total agree)
*N= nitrogen and P=phosphorus

5.3.4 Knowledge about eco-innovations and awareness for changes

During the expert interviews mostly those eco-innovations were mentioned, which are related to the use of organic fertilizers or to the closing of nutrient cycles. However, within the complete supply chain the knowledge of specific eco-innovations turned out to be rather limited and varied according to the eco-innovation itself and the different supply chain partners.

In **Figure 5-2** the level of knowledge of the three specific fertilizer eco-innovations (i.e. SNF, FG and SRMF) is shown. SNF is well known by all partners in the supply chain, with no significant differences in knowledge between the supply chain partners. This differs for FG and SRMF: For these two eco-innovations we found significant differences among the chain members, with knowledge levels decreasing downstream the supply chain. While FG is known by all producers, about 65% of the traders report that they are aware of this eco-innovation and only about 30% of the farmers, whose knowledge is significantly lower. SRMF is an eco-innovation relatively well known only by fertilizer producers (60%), by contrast less than 30% of the traders and the farmers know about it. The non-parametrical comparison showed significant differences between the producers and trader and farmers. Interestingly, farmers who directly would be able to apply the eco-innovations in their daily business have the lowest knowledge about the different options.

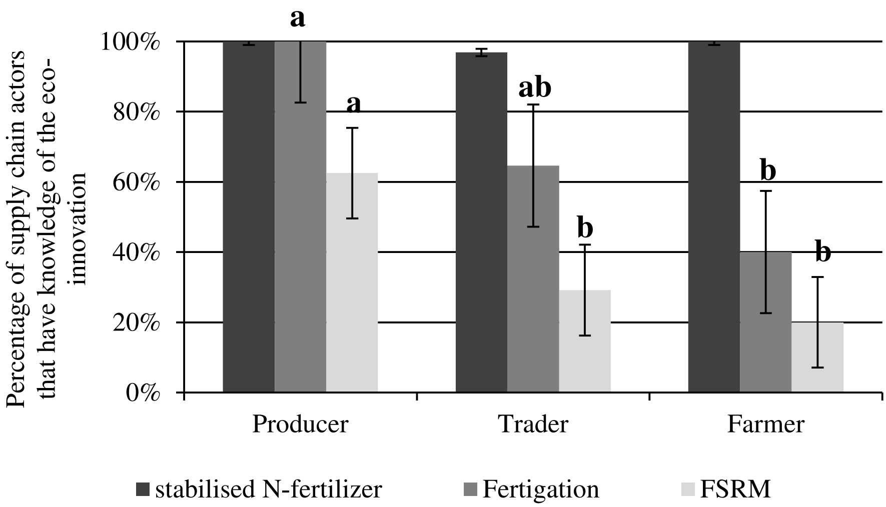

Figure 5-2 Knowledge of three fertilizer eco-innovations (bars show standard deviations; a and b indicate significant differences between the single supply chain actors at $\alpha \leq 0.05$, measured with non-parametrical-comparison using global ranks; SRMF: fertilizer made from secondary raw material).

5.4 Discussion and conclusions

This chapter contributes to the empirical literature focusing on the drivers of eco-innovation in the agricultural sector in general and the fertilizer supply chain in particular. Additionally, we include the influence of the supply chain position as drivers of eco-innovation and consider also the possibility that the effects differ across the supply chain levels by using basic principles of the innovation system framework. Furthermore we take an in-depth view on the adoption of eco-innovations within a supply chain position to get a better understanding on the dynamics and innovation capacity of eco-innovations in the fertilizer area.

Our empirical findings indicate that the adoption of eco-innovation is rather motivated by **technology push** than a strong **market pull** of farmers, which might change if retail or consumers would honor the use of eco-innovations with a higher willingness to pay. Farmers are positioned at the beginning of the food supply chain, but their market power is rather weak due to the dominance of the retail sector. Although they are the producers of agricultural goods, they have relatively little influence on consulting or production companies. As a consequence, farmers actively adopt only few changes themselves because they rather passively depend on their suppliers and their customers. There are evidently significant gaps between expert expectations (policy-makers, researchers, extension workers, etc.) and farmers' perspectives, needs and opportunities (Totin et al., 2012). That leads to the conclusion that it is sufficient to motivate "technology push" and "market pull" within the whole downstream fertilizer supply chain by creating a pull for eco-innovations accompanying the technology push of the research intense producer level. Clearly, much can be done with existing resources and already developed techniques, but a wider transition towards a more environmental friendly agriculture will not occur without some external incentives (from government or R&D). Hence, market pull factors play only a moderate roll for the adoption of eco-innovations. The farmers alone are neither in the position to trigger the use nor pro-actively develop any eco-innovations.

To assess the **perceived need** for action across the supply chain as a driver for eco-innovations we conclude that market demand, measured by the awareness to take action is moderate and differs according to supply chain position. In contrast to Heemskerk (2005) in our study fertilizer producers and traders estimate the demand of the farmers for more environmental friendly innovations as very low. In general fertilizer producers and farmers are aware that changes in the production and application of fertilizers are necessary, because fertilization is, as nearly all agricultural practices, highly depended on environmental conditions. Climate change will affect the German fertilizer market (Olesen and Bindi, 2002). More extreme weather conditions (e.g. drought conditions within the periods when fertilizers are applied (Schönthaler et al., 2015) could lead to a shorter timeframe for fertilization or different application strategies and/or forms of fertilizers. However, although farmers indicate that they are aware of the need for action, they will not move as long as there is no clear economic stimulus. Here all members of the supply chain should be aware of the need for improvements. All supply chain partners in our investigation agree that environmental **regulations** will become stricter, which could lead to a faster adoption of eco-innovations. These findings confirm previous studies in the field of eco-innovation (Brunnermeier and Cohen, 2003; Horbach, 2008) indicating that environmental regulations have a positive impact on adoption. The respondents are sure that with the implementation of CAP 2020 (European Commission, 2013) political change will occur that may lead to restrictions in mineral fertilization to reduce unwanted nutrient losses. However, more strict regulations can also result in a situation that a product like SRMF cannot be used in Germany any longer, because of stricter regulations (e.g. hygienic aspects, lower threshold values for heavy metals or organic pollutants). The technical progress in this area indicates that most of the basic materials are useable in the next couple of years (de-Bashan and Bashan, 2004). One solution could be that the government might step in by honoring these technical processes and/or by providing some sort of guarantee for the needed extra investments. Moreover, as far as we concerned, legal regulation could go further to promote public-private certification such as EMAS or ISO14001 (ISO International Standard, 2000; EMAS, 2009), instead of relying only on subsidies or tax incentives to encourage the use of eco-innovations. However, literature indicates (Narrod et al., 2009) that the promotion of standards requires changes in forms of collective action and must include the whole fertilizer supply chain.

The general **knowledge** about fertilizer eco-innovations seems to strongly decrease downstream the fertilizer supply chain. One possible explanation for the relatively low knowledge concerning the eco-innovations SNF, FG and FRSM at farmers' level is that the market diffusion of these technologies is relatively low. All three of them are fully developed, but all are facing acceptance problems. There might be various reasons for that: SRMF can only be used in accordance with the German fertilizer regulations concerning organic materials as base material for fertilizer production or fertilizer usage, which excludes rather cheap materials like blood, bone and animal waste (DüMV, 2012). Furthermore, the basic materials are traded from other sources, bypassing the original fertilizer supply chain especially skipping the fertilizer producers. This means that particularly the producers are not willing to promote these fertilizer materials. FG requires extra capital for irrigation equipment and the irrigation infrastructure is necessary, both are connected with high investment costs at farmer's level. The fertilizer products which can be used in FG needs to be processed differently (to avoid clogging), which leads to extra investments in production. SNF has the highest market share, but still is a niche product because of its higher costs (app. 20-60% more expensive) and lower availability at trader level compared to other fertilizer products. Additionally the production of these fertilizer products is much more complex and requires a proper technical know-how and a more specialized production factory, which could lead to production places in Europe or other Western countries with higher salaries and ecological standards making the production even more high-priced. All three eco-innovations could expand their market shares if regulation or society pressure will further restrict the acceptable nutrient surplus at farm level. For policy makers interested in growing innovative activity in agriculture, we find that building a farm's adoption capacity through knowledge acquisition and assimilation is very likely to increase the adoption of eco-innovations.

Moreover, because of the complex agricultural working situation farmers heavily rely on consulting and therefore may have a lower knowledge of eco-innovations. The trader level especially seems to act as a bottle neck. Traders can play an essential role asking for new ways of plant production and fertilizer application by only accepting agricultural goods under certain prerequisites (cultivation contracts, priority trading, etc.). However, at the moment there seem to be little incentives for traders to be involved in the environmental discussion. In addition, the multiple players in the German fertilizer supply chain are not very well connected, rather fragmented and mostly act very regional. To create a stimulating environment for the adoption of eco-innovations it is absolutely necessary for the whole supply chain to encourage lifelong education and an active information exchange. As agricultural production worldwide continues to increase in complexity, this indicates there may be greater value in establishing networks with peers, local suppliers and customers as well as other local institutions for gaining awareness of new technologies and practices (Sligo and Massey, 2007; Klerkx et al., 2010; Lambrecht et al., 2015). Many eco-innovations are already in a very developed stage of the innovation life cycle, but because of lack of knowledge and communication channels, they are often not well-known. Education and knowledge sharing among all actors of the supply chain would be necessary to improve the overall environmental performance. Regular seminars and workshops on new technological and market developments in agriculture for farmers and traders would therefore be more than desirable. Mylan et al. (2015) showed that the effectiveness of various eco-innovation mechanisms is shaped by pre-existing supply chain structures. They claimed more integrated supply chain and existing degrees of collaboration make it easier to promote eco-innovations. Additionally their studies showed, that the distribution of eco-innovations needed a shift in supply chain governance modes (more cooperative) and the effective use of innovation coordination mechanisms (information exchange, collective framing of sustainability issues, etc.). Solutions at farm level for adoption of eco-innovations might be practice sharing, flagship projects and guidance documents. However, due to the relatively small size of agricultural trading organizations and the rather local focus, every single trader must find a solution which is suitable for their surroundings.

All eco-innovations described in this paper can be used to improve the overall supply chain performance and lower the environmental impact of fertilizer use, but all of them have one main barrier, namely that in the first phase they are more expensive than existing alternatives. Numerous other eco-innovations are already on the market (e.g. precision farming technologies), but the pressure of using them is still too low. All four drivers investigated in our paper have the potential to force the use of these eco-innovations, but there are at least not yet strong enough to achieve real differences.

In conclusion our study can be seen as a first step to understand the adoption of eco-innovations from a supply chain perspective. However, this study still has a mere exploratory character as it is restricted in sample size and questionnaire design (stemming from exploratory statements). Additionally we only focus on incremental eco-innovations which do not change the agricultural system and fertilization itself. It would be interesting to evaluate if the low knowledge and engagement of farmers are also true for more fundamental innovations (e.g. GMOs). Hence, a follow up based on a larger sample and a more focused questionnaire design looking only at one specific driver (e.g. knowledge) would be desirable.

6. Discussion and conclusions

The main objective of this work is to gain advanced knowledge of the environmental impact of fertilizers and to identify possible improvements. This Chapter discusses the main findings and outlines general conclusion by answering the main research question.

Several theories have been employed on the interaction between the requirement of innovations in the fertilizer sector and the innovation adoption at farm level. In Chapter 2 a life cycle assessment (LCA) has been used to focus on the environmental impact of mineral fertilization. In Chapter 3 the carbon footprint calculations helped to specify the greenhouse gas emissions of mineral nitrogen fertilizers and relevant alternatives. In Chapter 4 a systematic literature emphasized and characterized the main drivers and barriers of innovation adoption and diffusion in the plant nutrition area. Finally Chapter 5 provides a supply chain perspective of the necessity of eco-innovations and the knowledge distribution of eco- innovations within the German fertilizer supply chain allowed new insights concerning the innovation adoption of agricultural supply chains

Furthermore to the theoretical contribution and main conclusions (6.1), scientific contributions and limitations for future research are given (6.2), before concluding with the practical implications for scientist, practitioners and policy makers (6.3).

6.1 Main findings and conclusions

The production, use and application of fertilizers have considerable impacts on the environment, seen as eutrophication, nitrogen in groundwater bodies, soil acidification or the use of scare resources. However, fertilizers are important to maintain soil productivity and crop yields feeding nowadays more than 7.5 billion people (United Nations, 2015). The overall objective of the present thesis was to identify the key factors in consideration between the environment impact of fertilizers and its continuous use, cumulated in the main research question:

Main research question

To what extent can the environmental impact of fertilizers be improved by accelerating the adoption and diffusion of eco-innovations within the fertilizer supply chain?

The present thesis discusses the environmental impact of fertilization and the adoption of fertilizer innovations by using different theoretical perspectives. The life cycle perspective is used to evaluate the environmental impact of mineral fertilizer itself. The carbon footprint perspective describes the greenhouse gas emissions of different mineral fertilizer and fertilizer alternatives in order to find possible better solutions for fertilization. The perspective of different drivers and barriers on the innovation adoption in the fertilizer supply chain tries to give more detailed answer to the question of the low innovation adoption in the fertilizer and agricultural sector. The supply chain perspective on knowledge sharing and different options on the need for eco-innovations is used to get a better inside view on the innovation adoption and rejection within the fertilizer supply chain concludes this thesis.

6.1.1 The environmental impact evaluated by life cycle assessment

Chapter 2 takes a first step in answering the general research question by outlining the environmental dimension of the research. However, the contribution of the fertilization to the environmental impact of agriculture and agriculture products is still on debate. Many examples of agricultural LCA calculations get to the conclusion that fertilization in general and nitrogen fertilization in particular, results in high emission for the categories climate change, fossil fuel depletion, acidification, eutrophication and resource depletion (Brentrup et al., 2000; Brentrup et al., 2004b; i Canals et al., 2006; Blengini and Busto, 2009; Gilbert et al., 2011; Cellura et al., 2012b; Torrellas et al., 2012). It is still unclear if these emissions are stemming from the fertilizers itself or other external inputs or processes of agricultural production. In response to this research gap, Chapter 2 answered the following research question:

Research question 1: *Is it possible to observe differences in the environmental impact between different mineral fertilizers (1.1) and mineral fertilizer product types (1.2)?*

The LCA calculations in Chapter 2 try to estimate the divergence in research of agricultural production on the one side and fertilization on the other side. By focusing the environment calculations to a very well-researched and highly accepted method, the LCA, other uncertainty factors are irrelevant and the results should be reliable. The LCA study focused on the three main nutrients nitrogen, phosphorus and potassium instead of only looking on the impact of nitrogen in agricultural production systems as many other agricultural LCA studies. By excluding the field emissions during the cultivation period, many other external variables influencing the LCA results were eliminated from the considerations in this thesis. Abalos et al. (2014) as well as Bouwman et al. (2002) showed, that irrigation, cop type and extreme weather scenarios after fertilizer application have also significant effects on the emission of agricultural production systems making the distinction of the direct fertilizer related emissions even more difficult.

The calculations in Chapter 2 conclude that the mineral fertilizer types as well as the production types (complex vs bulk blend vs single nutrient) play a significant role shaping the environmental impact of the fertilization. This was also shown for nitrogen mineral fertilizer types (Smith et al., 2007; Smith et al., 2008; Snyder et al., 2009). The calculations in this thesis goes one step further by working out that even the type of phosphorus fertilizer can have a significant impact on the LCA results. For the investigated impact category “climate change” the results reveal that a fertilizer made of urea, muriate of potash and triple-superphosphate is the best solution. In the impact category “fossil fuel depletion” a mixture of calcium-ammonium-nitrate, muriate of potash and diammonium phosphate leads to the lowest value. For the impact categories “acidification”, “eutrophication” and “resources depletion” no significant differences could be detected for both nutrient compositions and all fertilizer product types. Obviously it is rather difficult to access which is the best choice in terms of fertilizer types and products just based on LCA calculations. Therefore, a scenario analysis of newer production technologies was used to get more reliable results. Here the results significantly showed that urea is, in terms of emissions in the category "climate change" during the production worse than other mineral nitrogen fertilizers.

It can be concluded, that LCA calculations can play an important role by estimating the environmental impact of agriculture itself or specific agricultural products. Here main sources of harmful emissions can be detected and possible solutions for lowering the environmental impact by the sensitivity analysis gives further hints for more environmental friendly solutions. However, this depends highly on the accuracy of the calculations and the input data. The LCA calculations in Chapter 2 significantly showed that there is a possibility to even lower the environmental impact of the fertilization with very simple actions like using a different fertilizer type (e.g. urea vs ammonium nitrate) or product type (complex vs. bulk blend).

Overall, the results of the LCA do not provide any black-and-white decision of what is best in terms of fertilization. However, with modern production techniques in developed countries, urea should be used with special care. Complex fertilizers reduce the workload, but always range in the posterior area in terms of emissions in all categories. A blended mixture between single nutrient fertilizers, without urea as nitrogen component, can reduce the workload as well as the environmental harmful emissions. However, blended fertilizer can have the disadvantage of getting separated during transportation and application leading to different nutrient rates at field level.

6.1.2 The environmental impact evaluated by the carbon footprint

Chapter 3 goes one step further on the examination of the environmental impact of fertilizer focusing on the most important emissions of fertilizers, i.e. the emission of greenhouse gases. Many studies focusing on greenhouse gas emissions within agricultural production in general and in crop production in particular blame especially the nitrogen fertilizer (organic and mineral) for high emissions (e.g. Bouwman et al., 2002; Hao et al., 2001; Scheer et al., 2008; Smith et al., 2007). In the IPCC greenhouse gas inventory an extra chapter on N_2O emissions from managed soils and CO_2 emissions of fertilizer applications is compiled because of the importance of this topic (De Klein et al., 2006). Most of these studies only compared mineral with organic fertilizers or use only one source of nitrogen for the calculations. Smith et al. (2008) and Snyder et al. (2009) both show that the type of mineral fertilizer (urea, ammonium nitrate, calcium ammonium nitrate and urea ammonium nitrate) have different levels of greenhouse gas emissions after the application. However, combining the data of the fertilizer production, with the data of the greenhouse gas emission and extend these calculations to other fertilizer products (stabilized nitrogen fertilizers, fertilizers made from secondary raw materials and as well as alternative application techniques (i.e. fertigation)) is a completely new approach with should answer research question 2:

Research question 2: *To what extent do eco-innovations reduce the carbon footprint of fertilization?*

Chapter 3 aims to extend the work on the environmental impact of mineral fertilizers and fertilizer alternatives to get a better overview of the possible greenhouse gas mitigation in agriculture. Restricting the calculations only to the emissions of greenhouse gases places the main emissions of fertilizer production, use and application into focus. Additionally the use of fertilizer alternatives as a comparison links it to the actual discussions of how to lower the environmental impact of agriculture without losing productivity. However, all considered scenarios need to reflect the actual agricultural situations. The considered eco-innovations do not change the farm management systems and consequently are easily introducible to farming practices. With an addition of the use of irrigation in agriculture it is also considered regarding the fact that irrigation will be more relevant in the next couple of years in many European agricultural systems (Olesen and Bindi, 2002).

The carbon footprints of the assessed mineral fertilizers vary between 1300 kg for ammonium nitrate and up to 1460 kg CO_2-equivalents for urea ammonium nitrate. For the stabilized nitrogen fertilizer with urea the urease inhibitors seem to be less effective (-2%) compared to a combination of urease and nitrification inhibitors (-14%). The carbon footprint was reduced by 17% for ammonium nitrate application combined with the nitrification inhibitor dicyandiamide. Application of mineral fertilizers via irrigation reduces the carbon footprint of mineral fertilizer only slightly for ammonium nitrate (- 4%), but to a greater extend for urea (- 20%). The carbon footprint calculation for feather meals and leguminous crops meals resulted in 10-20% higher values than mineral fertilizers. Meat-and-bone meals even have a 120% higher carbon footprint.

Stabilized nitrogen fertilizer using a combination of urease and nitrification inhibitors can reduce the greenhouse gas emission of nitrogen fertilizers. However, they have one big disadvantage. These kinds of fertilizers are much more expensive. As long as there is no clear stimulus, by policy, society or consumers, farmers are not very willing to adopt them. Fertigation, as long as the fertilizer quality provides it, is not only from a labor point of view, but also from an environmental point of view preferable. Fertilizers made from secondary raw materials all have higher emissions with respect to greenhouse gas emissions. However, they use already produced materials and can therefore help to close and maintain sustainable nutrient cycles. However, only byproducts of other agricultural or industrial productions are useful for nutrient recycling. Producing these materials only as fertilizers replacement is not effective.

6.1.3 The adoption of different types of eco-innovation

Based on a literature review Chapter 4, tries to explore the eco-innovation adoption by different types of innovations and the main drivers. Numerous innovations have been designed in the fertilizer and plant nutrition area in the last decades (see Renni and Heffer, 2010). However, the adoption and acceptance at farm level and by individual farmers of many new products and techniques is still inadequate (Sunding and Zilberman, 2001; Marra et al., 2003). To get a better inside view, the literature was split up in disruptive and continuous innovations as well as in product and process innovations and in innovations of other types. The aim was to get more specific answers to the research questions 3:

Research question 3: *Have different types of eco-innovations different problems to diffuse throughout the fertilizer supply chain?*

Chapter 4 tries to transfer main results of research in innovation diffusion to the agricultural sector in general and the plant nutrient area in particular. Here major theoretical contributions from the technology acceptance model (Davis, 1989) and the extended technology acceptance model (Venkatesh and Morris, 2000; Venkatesh et al., 2003) were combined with theories of innovation types and drivers of the innovation adoption (e.g. Diederen et al., 2003; Negro et al., 2012). It was aimed to get a sharpened picture of the nature of innovation adoption by farmers. The goal was to come to a more general framework which aims to explain the main drivers of innovation adoption at farmers' level for each specific type of innovations. The technology acceptance model (TAM) was extend by 17 variables expressed as external precursors, factors suggested by other theories, and so called contextual factors, in order to find universal explaining variables which can push the innovation adoption. Afterwards, 91 publications in the field of fertilizer innovation adoption, diffusion, transfer and acceptance were splitted into the specific type of innovation and then the main drivers were estimated.

Based on the literature review, the quality of support and information can primarily support the eco-innovation adoption within the fertilizer sector. More disruptive innovations can additionally be stimulated by a younger age of the farmers, a higher education level and greater farm size, because all these variables increase the planning horizon and decrease the breakeven point. Continuous eco-innovations are more pushed by information about these specific innovations and the access to credit to support the purchase. Many fertilizer application technologies have often already reached a high level of acceptance in developed countries, but they are still rather unknown and not widely used in developing countries (e.g. row application). That means the division between different agricultural environments is important to come to general relevant conclusions.

Generally speaking, the fertilizer supply chains must overcome homemade barriers like a lack of high-quality support and gaining access to new markets. This is especially remarkable because all these variables could be improved by the fertilizer supply chain itself. The recruitment of higher educated staff combined with a better connected training program, even across national boundaries, could make the fertilizer supply chain more open to new technologies, and new technologies could easier diffuse within similar agricultural systems.

6.1.4 Knowledge and adoption of innovation through the German fertilizer supply chain

In Chapter 5 the innovation adoption within fertilizer supply chains is concentrated on the German fertilizer supply chain. Hall et al. (2007) and Klerkx et al. (2010) showed that even a supply chain itself can be an innovative system promoting innovation or might be a barrier for innovation adoption on the individual level. With putting a new dimension to the innovation adoption within supply chains it was aimed to get better explanations for the lack of innovation adoption in agriculture. Additionally the problem of information flow within supply chains is dealt with in Chapter 4. Based on approaches from knowledge and information exchange in networks, it is evaluated if the fertilizer supply chain is well connected and informed or if it is too small structured and has a deficiency in getting information from outside the system.

Therefore, Chapter 5 tries to apprise about the clear requirement of new products to enhance the fertilization (1) and the knowledge distribution about new technologies along the fertilizer supply chain (2):

Research question 4: *How do different actors of the fertilizer supply chain perceive the necessity and knowledge of eco-innovations?*

To answer Research question 4 data were collected using 8 expert interviews. This was followed by a structured questionnaire with different experts from every step of the fertilizer supply chain, including researchers. Here the fact that knowledge can be a precursor for the innovation adoption or rejection was exploited for further consideration of the innovative potential of the German fertilizer supply chain. Using basics from the theory of innovation acceptance (Davis et al., 1989), the determinants of eco-innovations (Horbach et al., 2012) and innovation system thinking (Klein Woolthuis et al., 2005) a supply chain perspective on the perceived need for new developments within the German fertilizer supply chain was conducted. With the supply chain perspective it was aimed to get a more general view on the innovation adoption within agricultural supply chains compared to studies only putting farmers in focus (Diederen et al., 2003; Vanclay et al., 2013). The goal was to explain the innovation adoption within the German fertilizer supply chain with theories which do not concern the individual adoption (e.g. Davis, 1989; Rogers, 2003) trying to come to a better explanation for the lack in adoption. Eco-innovations as basic innovations were used because they have to be innovative and reduce the environmental impact of the fertilization. Therefore, they have more than one dimension in order to develop a more sustainable agriculture.

The knowledge about specific fertilizer innovation decreases along the fertilizer supply chain. This is an important fact, because farmers are mostly the only users and consumers of fertilizer innovations. However, concerning more general questions about the future of fertilization and agriculture itself, farmers are much more concerned than the agriculture traders. All farmers are afraid of more frequent extreme weather scenarios and restrictions concerning nitrogen and phosphorus fertilizer use. At the agricultural trading step, these concerns are much lower. All members of the supply chain agreed that they are not first users of new technologies and that new technologies are only slightly better than older ones. These findings indicate that the whole fertilizer supply chain is not the most pioneering supply chain in the agricultural sector.

Summarizing the findings of Chapter 5, it seems that the fertilizer supply chain has problems in changing to a sustainable agriculture supply chain. However, there is potential for future developments. Some new technologies (e.g. stabilized nitrogen fertilizers) are already known by a majority of the supply chain partners. That indicates if a new technology reaches a certain market penetration, the knowledge about this technology quickly diffuses through the fertilizer supply chain and could easily gain high adoption levels. All considered eco-innovations can help to come to a more sustainable agriculture. However, as seen in Chapter 3, they do not change the greenhouse gas emissions as good as promised.

6.2 Theoretical and methodological contributions

A wide variety of books, scientific articles and publications has been devoted to investigating the link between the environmental impact of fertilizers and the need to develop new technologies and products to its improvement. This book focuses on the interface between the environmental influence of fertilizers and the economic nature of innovation adoption within the fertilizer supply chain to estimate the environmental impact of the fertilization itself and possible solutions for the fertilizer sector. This is addressed by the main research questions of this thesis.

Main research question with an environmental context

To what extent is it possible to reduce the environmental impact of fertilizers without changing the farming management system?

Overall, the study evidences an increasing importance of a better connection and understanding of the environmental dimension within the (German) fertilizer supply chain.

First, as Chapter 2 and Chapter 3 showed fertilization needs to be adopted more to the regional, climatic and specific farming surrounding conditions. With only few adjustments in timing, fertilizer type or application method, unavoidable loses to the environment can significantly be reduced. Here a new product like stabilized fertilizers can help to reduce these loses combined with adopted management strategies or new application techniques. These eco-innovations, mostly created by the pressure to reduce the environmental impact, are usually more expensive, the usage is more complex, special equipment is needed or the purchase is not as easy as for standard products. To create a fruitful environment to adopt these new technologies, these measurements needs to be combined with a good quality support and regular training (e.g. like workshops, field days or exhibitions), where farmers can acquire new knowledge about these kind of technologies.

Second, all supply chain members need to take the concerns and difficulties of farmers to maintain plant productivity without generating losses to the environment seriously. It is not helpful for the whole discussion cycling around the environmental impact of agriculture to always blame the farmers for all negative impacts. All parts of the fertilizer supply chain are responsible to lower emissions and maintain soil productivity as mentioned in Chapter 4. Here a better connecting of all supply chain steps, even with the researchers at universities or national research institutions is desirable to create faster and better solutions for problems the fertilizer supply chain is confronted with.

Collaboration and lessons learned by other agricultural supply chains might help to stimulate the eco-innovations generation. However, innovations in fertilization should always acknowledge that they also have to reduce the environmental impact and not only increase the yield and product quality.

Based on the different perspectives and theories used in this thesis, the main findings reveal that there are several barriers along the fertilizer supply chain that must be resolved in order to come to a more sustainable fertilization in more than just the environmental dimension. Therefore the research was again divided into a research question focusing on the innovation management context of the problems faced by fertilization:

Main research question with an innovation management context

How can the diffusion of eco-innovations be improved within the fertilizer supply chain?

This dissertation provides further details to draw a profile on the nature of innovation adoption within agricultural supply chains. In Chapter 4, it was shown that many barriers are similar in developed and developing countries, leading to the conclusion that these barriers could be universal for many agricultural chains. Consequential farm size, quality of support, education, labor requirement, access to market and credit as well as regulation could hinder or stimulate the innovation adoption.

As outlined in Chapter 4, the knowledge exchange between all supply chain members needs to be fluently and the information flow needs to be in both directions, upstream and downstream in order to maintain a fruitful setting for the development, diffusion and adoption of new technologies, application methods or fertilizer strategies. A productive supply chain, as for example in many technology or industrial production processes, is only generated, if information flows homogeneously from one end to the other. Additionally, the fertilizer supply chain must constantly educate all stakeholders.

To answer the main research question focusing on a supply chain perspective one can say that many of the problems the fertilizer supply chain is facing at the moment are mostly homemade. By encapsulate the R&D from many other agricultural areas the fertilizer supply chain now lacks in collaboration and partnerships. Especially the variables education level, quality of support and labor requirement were found to be significant for the innovation adoption (Chapter 5) but all can be managed by the fertilizer supply chain itself.

6.2.1 Scientific contributions

The present study focused on the production and application of fertilizers mainly in Germany and therefore primarily applies to this specific sector. At the same time the results of the study can be extrapolated to a more general view on agriculture supply chains and sectors. The present study provides more insight into the environmental impact of fertilizers and the nature of eco- innovation adoption within supply chains, which can be easily adopted by other agricultural supply chains. In the following, the scientific contribution of the applied theoretical methods are shortly explained and contoured.

The LCA calculations presented in Chapter 2 are an extension of many agricultural LCA studies conducted in the last couple of years. Since many agricultural LCA studies came to the conclusion, that the production, use and application of fertilizers are a major problem for the environmental impact of agriculture in general it is astonishing, that there are no more studies on fertilizers and fertilization. What is even more amazing is the fact that all existing studies are based on data collected in a period prior to the year 2000. Since manufacturing and production has sustainably changed in (e.g. filter technologies and recycling), it would be naïve to assume that these changes did not take place in the area of fertilizer production and manufacturing. Regarding the fact that more than 80% of the publications concerning LCA studies in agriculture listed in ISI Web of Knowledge(SM) have been published after 2007 it arise the question of data quality. Additionally those LCA calculations already published in the area of fertilization are not very suitable for the estimation of the impact of (mineral) fertilizers alone. Davis and Haglund (1999) are the only one who published exact data of the fertilizer production and transportation, but not going any further and leave out important factors like the emissions direct after the fertilizer application and newer production technologies. Skowrońska and Filipek (2014) reviewed different LCAs of fertilizer calculations. However, their review is nearly only based on agricultural LCA calculations with different system boundaries and end products (e.g. the production of barley, wheat and extensive or intensive production) making a real estimation of the actual impact of the fertilizers nearly impossible. Wood and Cowie (2004) only reviewed greenhouse gas emissions in the fertilizer production as well as Smith et al. (2008) who only estimated the role of fertilizers in the greenhouse gas mitigation in agriculture. Numerous other agricultural LCA calculations (e.g. Brentrup et al., 2004b, Nemecek et al., 2011 or Cellura et al., 2012) reviewed the role of fertilizer in the whole agricultural production system in one way or the other, however here fertilizers are only one of many inputs making a real assessment of the impact much more difficult.

The carbon footprint presented in Chapter 3 is not a completely accepted scientific method to examine the greenhouse gas emissions. However, as long as there is no scientifically approved method, it is an alternative to a full LCA calculation to get the attention of policy makers, consumers and interested persons. It would be desirable to create a standard calculation method, a clear standard for the system boundaries and a fixed end unit for the carbon footprint itself. That could make it more reliable. In this way people could better understand the consequence of everyday life, actions and decisions. The calculations in this thesis show that there are possible reductions of greenhouse gas emissions even within the small field of mineral fertilizers. For a start to a better general understand of the term sustainability and sustainable agriculture the tool carbon footprint can be very helpful. As Berry et al. (2008) mentioned:…*Sustainability trade-offs are often complicated and, in many cases, not fully understood. There is a danger* *that simply providing information may increase consumer confusion and ultimately lead to a backlash against the goal of sustainable consumption.* Here easier to understand and still scientifically supported labels could help to get a better consumer understanding of pricing in favor of environmental protection.

The literature review presented in Chapter 4 leads to new perspectives in the consideration of eco-innovation adoption in agricultural chains. Here new ways of finding drivers by estimating the type of innovations in a literature review even in existing studies can expand the knowledge of the nature of innovation adoption within agricultural supply chains. By extending TAM with external precursors, factors suggested by other theories and contextual factors, a series of drivers were tested and evaluated for the usefulness as general variables for the eco-innovation adoption in a very early stage of the innovation adoption process. With evidences from this very early state of innovation adoption, it was aimed to find confirmation to speed up the innovation adoption in the fertilizer sector and to refocus it. Because all eco-innovations considered in this thesis are still in a very early phase of diffusions, some even did not diffused at all, despite all efforts of policy makers and producers. Here the new framework used in this work could help to see problems within specific supply chains and types of innovations more clearly. The framework by using an extended TAM and different types of innovations can easily be adopted by other scientists looking on innovation adoption even beyond the agricultural sector.

The examination of knowledge sharing used in Chapter 5 can provide a good inside view on the understanding of information flows within agricultural supply chains. Future studies could examine the link between knowledge sharing and possible innovation adoption making forecasts for new agricultural products even more reliable. Additionally, the studies in Chapter 4 on the requirement to change according to climate change, regulations or new technologies, provides a new inside view of the different preferences of the supply chain members. Combined, both methods provide a new approach on the understanding of innovation consideration in agricultural supply chains. Knowledge can be seen as a precursor for innovation adoption (Tepic et al., 2012; Totin et al., 2012; Aguilar-Gallegos et al., 2015), which needs to be evenly distributed. That can be easily tested in other supply chains. Here simple questionnaires on the knowledge of specific innovation could come to a very good explanation for low innovation adoption in all kind of supply chains.

6.2.2 Limitations and directions for further research

The results of this study have allowed us to draw important general conclusions as stated above. Nevertheless, some of the general assumptions made in this thesis should be regarded with some caution. In the following the main limitations and solutions how they could be addressed in future are briefly outlined.

The LCA calculations in Chapter 2 have some major weaknesses, which concerns nearly all agricultural LCAs. First, the input data of the LCA calculations are, especially regarding the data of fertilizer production and manufacturing, rather old and not adjusted to modern production technologies. Additionally, nearly all LCA calculations in agriculture are based on very few databases (Agri-Footprint, ELCD, Ecoinvent, GaBi and Probas), which do not update fertilizer data regularly. Continuous data supply by fertilizer manufactures and national as well as international research institutions would be desirable. Furthermore new LCA calculations, which also include the effect of the emissions and outputs in longer perspectives, are necessary. There are methods including a time horizon of more than 100 years to estimate the damage to the ecosystem, human health and economy. However, since on the decade 2000-2010 no major theoretical developments have been established (e.g. Bare et al., 2000; Bare et al., 2008). Additionally the lack of very regional data is a big concern regarding agricultural production. Because agriculture is very regional and soils, climate and environmental conditions differ on very small scales, regional data for many agricultural situations are needed. For the Western-European countries, the USA and Canada, the data bases are satisfying. However for Eastern-European countries and even more for Latin America, Africa and Asia the data base is rather limited. Furthermore, the calculation methods with many standard values for the emission after application can be questioned. Field experiments with a number of different fertilizer type alternatives and fertilizer production types, in clear and scientific publications could extremely extent the reliability of LCA and environmental calculations, making these methods even suitable as basis for costumer labels or policy decisions.

Many LCA studies are restricted on emission concerning nitrogen fertilizers. However the calculations in this thesis showed that even phosphorus can have a significant effect on the LCA results. Especially regarding the fact, that phosphorus is a finite resource and the environmental harm in the category resource depletion will become even more important.

The carbon footprint used theoretical approach in Chapter 3 needs an ISO-norm and better and more focused definition to be part of the scientific understanding of greenhouse gas emissions.

The eco-innovations covered in Chapter 3 and 4 only focused on improvements which do not change the farming management system. Here an expanded view of more fertilizer and agricultural innovations could have widened the picture of innovation adoption within agricultural supply chains. Additionally it would be desirable if more farmers had participated in the survey to get a better overall view of the German fertilizer supply chain. To get a better overall picture, a comparison with other countries or other agriculture supply chains could be useful.

Especially in the area of innovation exploration in agriculture, it would be desirable if more scientists would use models of innovation adoption and acceptance. There are many publications concerning innovation adoption in agriculture, however, only a minority clearly defines the model, theory or scientific approach, making the whole field of innovation adoption in agriculture less scientific as it could be. It was very unsatisfying to find a large amount of scientific literature with no clear theoretical background or underlining theories about innovation adaption, diffusion, transfer and acceptance.

The framework used in Chapter 5 is an extend model and have therefore the same criticism as other extended models like the TAM2 (Venkatesh et al., 2000) or the UTAUT (Venkatesh et al., 2003). Here, above all, the critic is that all models are so extended that they will provide any significant correlations just because of the pure number of accessed variables.

6.3 Managerial and policy implications

The aim of this thesis is to increase our understanding of the environmental impact of fertilization and to create possible solutions from the management of eco-innovations. These results can be used by agricultural trading companies, farmers or policy makers to increase their knowledge about the environmental impact of mineral fertilizers and aiming an open and better understanding of possible connecting factors for the eco-innovation adoption. When more stakeholder in the fertilizer supply chain are open to new technologies, technologies changes or help to create innovations, better fertilizer application methods or practices have better changes to spread out and have an effect even without political measures.

6.3.1 Agricultural traders

As the Chapter 4 showed the trader step was, for the examined eco-innovations, a barrier in the knowledge-flow between the fertilizer supply chain members. That is especially of relevance, because of the complex agricultural working situation farmers heavily rely on consulting and therefore may have a lower knowledge concerning innovations. Education and knowledge sharing among all actors of the supply chain would be necessary to improve the overall environmental performance. Regular seminars and workshops on new technological and market developments in agriculture even for traders would therefore be desirable. Additionally traders need to be open minded for new developments and ideas within their whole working live, because traders can play an essential role in diffusing new ways of plant production and fertilizer application. However, than the trader step is obliged to have outstanding knowledge about these new technologies and innovations. This could have effects on the training and further education of the trader step of agricultural supply chains. Here a rethinking of the reputation and the education of agricultural traders seems necessary. A better education and live long learning can also help to overcome structural changes and avoid becoming irrelevant as supply chain step within the fertilizer supply chain. In addition, the multiple players in the German fertilizer supply chain are not very well connected, rather fragmented and mostly act very regional. To create a stimulating environment for the adoption of innovations it is absolutely necessary for the whole supply chain to encourage lifelong education and an active information exchange. As agricultural production worldwide continues to increase in complexity, this indicates there may be greater value in establishing networks with peers, local suppliers and customers as well as other local institutions for gaining awareness of new technologies and practices. In addition encouraging private participation of national research institutions or agencies within the fertilizer supply chain could give new impulses for the further development of a sustainable supply chain.

Additionally scientific facts must not be ignored because of personal attitudes. Chapter 4 displayed that many agricultural traders assume that climate change is more a fiction than a fact, which disagrees with a high number of publications in all areas of science. Here scientific journals, regional journals and studies from different universities, higher education institutions or national and international research institutions can be a good source of information.

6.3.2 Farmers

Framers can trigger innovations and even their development, by generating specific demand for them. Therefore they need specific platforms where farmers discuss problems and potential solutions with researcher or fertilizer producers to come to more targeted solutions. That could be blogs, apps, journals or internet platforms, which need regular updates and which are used by all members of the supply chain. Here all members of the fertilizer supply chain must take an active part not relying on the knowledge and the information of the preceding supply chain step. Because of their high education level it would be inefficient if farmers only rely on one consultant. Here a more open view of new contacts and information sources is desirable. A membership in different agricultural groups or co-operations could also help to create a better knowledge about new technologies and developments. Additionally farmers need targeted training opportunities to enhance their skills and knowledge so that they can cope with the complexities of the systems. Regular seminars, workshops or internet based tutorials could enhance the overall knowledge of farmers.

Farmers are mostly the user of innovations, fertilizers, application techniques and the producer of agricultural goods and services. However, most scientists are seeing them only as “executive body” that is not very willing to change. Sometimes researchers need to take the difficulties and concerns of farmers more serious, before starting new research projects and experiments. On the other hand farmers must be willing to try new techniques and developments.

6.3.3 Policy makers

Policy makers are recommended to support fertilizer or agricultural innovation by creating a fruitful environment for innovation creation and adoption. That can be by adjusting regulations and ordinances, a more suitable direct payment strategy or through other political and financial support. Nevertheless, it has to be in a way where farmers do not find these new regulations and guidelines as restrictions or harassment. Only if farmers are willing and open-mined in a voluntary process, the implementation of new techniques, innovations or stricter limits for nutrient surpluses are supported by a critical mass of farmers. Policy makers must find a compromise of support and regulation, leaving the everyday tasks to the farmers.

Many eco-innovations considered in this thesis (Chapter 3, 4 and 5) have the major drawback, that the R&D of fertilizer innovations is not very closely linked to other agricultural R&D. Here a better collaboration between the R&Ds specialized in fertilizers and fertilizers products and other agricultural areas to acquire, integrate and apply knowledge in their own R&D would promote and stimulate innovations which could be easier adopted by the farmers because they are more closely linked to their everyday task. Even the support of closely collaborate via public-private relationships could here help to can to a better innovation adoption.

However, the question remains, to what extend is the society willing to pay for a better environment or a more sustainable agriculture, because all political influence will come at a price. Here the policy makers also have the big task to decide which kind of agriculture will be supported. Worldwide or at least European perspective initial targeted subsidy schemes and strengthened public research on the systems for further improvement can lead to a more sustainable agriculture. However, the use of eco-innovations should also be enhanced, because they can be a first step for a sustainable agriculture.

Summary

Agricultural production has kept pace with the population growth (FAO, 2012). One major input for a productive agriculture are fertilizers. Despite their effect on yield and quality, they also have considerable effects on the environment leading to emission of greenhouse gases, acidification, eutrophication and use of scare resources (Ruttan, 2002; Kitzes et al., 2007). However, unlike other agricultural inputs, fertilizers cannot be substituted and a reduction in the fertilizer use can lead to major yield decreases or a production shifting to less suitable areas. In order to come to a more sustainable agriculture, these effects are not tolerable. By considering the above mentioned statements this thesis aims to expand the knowledge of the environmental impact and the sustainability of fertilizers in general and innovation supply chain thinking, knowledge exchange and innovation adoption within the fertilizer supply chain in particular with the main research question:

Main research question: To what extent can the environmental impact of fertilizers be improved by accelerating the adoption and diffusion of eco-innovations within the fertilizer supply chain?

To answer the main research question this thesis is divided into two main theoretical perspectives. The first part focuses on the environmental impact of mineral fertilizers and relevant alternatives. The second part focuses on innovation adoption concentrating on the German fertilizer supply chain which is then extended to a more global perspective.

Research focusing on an environmental perspective

Part one of this thesis focused on the environmental impact of the fertilization and its possible solutions. Numerous agricultural studies estimating the impact of agriculture via life cycle assessment (LCA) accuse (mineral) fertilizers to have a major effect on the impact categories climate change, acidification, eutrophication, fossil fuel depletion and resources depletion (e.g. Brentrup et al., 2000; Brentrup et al., 2004; i Canals et al., 2006; Blengini and Busto, 2009; Torrellas et al., 2012). However, all these studies have one major drawback. They look simultaneous on various agricultural inputs. Therefore, Chapter 2 takes a first step in estimating the environmental impact of the fertilization itself by answering the research question:

Research question 1: Is it possible to observe differences in the environmental impact between different mineral fertilizers (1.1) and mineral fertilizer product types (1.2)?

Here LCA calculations of different fertilizer types (e.g. urea, ammonium nitrate) and production types (single nutrient fertilizers, bulk blends or complex fertilizers) try to examine the amount of emissions during fertilizer production, transportation and application. With literature data of emissions during the fertilizer production, completed with data from expert interviews along the fertilizer supply chain a holistic LCA calculation was conducted. The results showed that especially urea should be used with special care in temperate climate zone and produced

with best production technologies. Additionally, the production and application of phosphorus should always be part of agricultural LCA studies, because this plant nutrient also can have effects on the results in the impact categories use of scare resources and salt water eutrophication. With an optimized fertilization strategy, the environmental burden can be reduced by up to 15%. As nitrogen application rates strongly affect the LCA results it is essential that the right amounts of nitrogen are used and that for nitrogen fertilizer production the best available technique should be installed. Furthermore, a careful consideration concerning the fertilizer product type should be part of every LCA of food and agricultural products, as this has a great impact on LCA results.

Chapter 3 focuses on greenhouse gas emissions. The aim of this chapter was to analyze to what extent existing eco-innovations in the German fertilizer domain might reduce the fertilizer carbon footprint without compromising on crop productivity. The carbon footprint, used with special care and an accurate developed framework, can be a good tool to estimate these greenhouse gas emissions (Finkbeiner, 2009; Hillier et al., 2009; Pandey et al., 2011). In agriculture studies, carbon footprint calculations culminated in a period between 2000 and 2010 (see Brenturp, 2009; Dubey and Lal, 2009; Hillier et al., 2009). Nevertheless, the carbon footprint is a good tool in estimating the greenhouse gas emissions and the effect a product or service could have on climate change (Weidema et al., 2008). This thesis used it as evaluation method to answer the following research question:

Research question 2: To what extent do eco-innovations reduce the carbon footprint of fertilization?

By calculating the carbon footprint with a basic LCA approach a scientific accepted method was used. The carbon footprint of different mineral fertilizers (urea, ammonium nitrate, calcium ammonium nitrate and urea ammonium nitrate), stabilized nitrogen fertilizers (using different inhibitors), secondary raw materials (feather meals, blood-and-bone-meals and leguminous crops meals) and a combined irrigation and fertilization were compared in order to find a more sustainable solution. Here especially the uses of a double inhibitor to delay the nitrogen transformation in the soils can have an effect on the carbon footprint results. All other alternatives result in very similar or even higher (feather meals and blood-and-bone-meals) carbon footprints as the ones for mineral fertilizers. However, the use of stabilized nitrogen fertilizers in Germany is very low, because of higher prices.

Research focusing on an innovation management perspective

The second part of this thesis concentrates on the fertilizer supply chain and the adoption of eco-innovations. Eco-innovations are one option to reduce the environmental impact of fertilizers without compromising on fertilizer productivity. Although numerous eco-innovations in the domain of fertilizers are available, they have no sufficient adoption rate. Chapter 4 tries a first step in explaining the low adoption of eco-innovation with agricultural supply chains in general and the fertilizer supply chain in particular. Numerous innovations have been designed in the fertilizer and plant nutrient area in the last decades. However, the adoption and acceptance on farm level and of individual farmers of many new products and techniques is still inadequate. Diehrend et al. (2003), Sattler and Nagel (2010) and Negro et a. (2012) explained some drivers as farm size, regulation or the education level which can stimulate the innovation adoption. Additionally the specific type of innovation was used to come to better predictions of the innovation adoption. Goal of the present thesis was to examine if the type of innovation has different drivers for the adoption through the fertilizer supply chain. This leads to the research question:

Research question 3: Have different types of eco-innovations different problems to diffuse throughout the fertilizer supply chain?

Here a systematic literature review combined with the types of eco-innovations within an expanded technology acceptance model (TAM) was used to estimate the main drivers. The study distinguishes between disruptive and continuous as well as process, product and other types of innovations to get a better understanding for specific situations. In this literature review, disruptive innovations are innovations which change the working process, use new technologies or support, whereas continues innovations only need small changes in the management system and require only minor new technologies (Boer and Gertsen, 2003; Markides, 2006). The distinction between the types of innovations was made, because it was assumed that the nature of the specific innovation influences the adoption. It was assumed that different drivers stimulate innovations in different agricultural environments. The results lead to the assumption that disruptive innovations are mostly pushed by a high quality support and a well-functioning information flow; continuous innovations are more pushed by a good access to credits and an informative environment.

Chapter 5 tries to explaining the low adoption of eco-innovation in the German fertilizer supply chain in particular. Numerous studies have shown, that only a combination of innovation system thinking and a proper knowledge sharing leads to a higher level of adoption of new or improved technologies or practices (Tepic et al., 2006; Totin et al., 2012; Aguilar-Gallegos et al., 2015). In this thesis theories of knowledge and information exchange in networks combined with basics from the theory of innovation acceptance (Davis et al., 1989), the determinants of eco-innovations (Horbach et al., 2012) and innovation system thinking (Klein Woolthuis et al., 2005) try to answer the last research question:

Research question 4: How do different actors of the fertilizer supply chain perceive the necessity and knowledge of eco-innovations?

Expert interviews along the fertilizer supply chain (researcher, producer, traders) and a detailed questionnaire with closed and open questions were used to estimate the necessity to change. Furthermore, the knowledge of different eco-innovations was used to evaluate the knowledge sharing of the fertilizer supply chain. Findings suggest that drivers for eco-innovations are perceived differently by the various actors in the fertilizer supply chain. The necessity to change the whole supply chain differs especially between traders and the rest of the fertilizer supply chain, with the traders being less optimistic and more fixed in their point of view. Overall knowledge on eco-innovations decreases downstream the chain. Chapter 4 shows that the fertilizer supply chain in Germany is very regionally located, making the diffusion of innovation through the complete supply chain even more difficult.

Fertilizers have an impact on the environment, however, the correct production type and fertilizer production type and a stabilization of the nitrogen can decrease these impacts and especially the emissions of greenhouse gases. The adoption of eco-innovations can be triggered by better information sharing between the single supply chain partners and a concerted promotion for the specific type of innovation.

The thesis concludes in Chapter 6 where the managerial implications have been translated into a number of recommendations for agricultural traders, farmers and policy makers.

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Appendices

Appendix Chapter 2:

Life cycle inventory assessment for all the application of all fertilizer product types (complex, bulk blend and single nutrient) with a nutrient composition of 17-5-13 (i.e. 17 % N, 5 % P_2O_5 and 13 % K_2O) and 15-15-15 (i.e. 15 % N, 15 % P_2O_5 and 15 % K_2O)

	17-5-13	**unit**	**com-plex**	**CAN/ MOP/ DAP**	**CAN+ MOP+ DAP**	**Urea/ MOP/ TSP**	**Urea+ MOP+ TSP**	**CAN/ MOP/ TSP**	**CAN+ MOP+ TSP**
Resources	Phosphate rock	kg	45.8	15.9	15.9	17.2	17.2	17.2	17.2
	Potash salt	kg	111.9	72.4	72.4	72.4	72.4	72.4	72.4
	Hard coal	MJ	238.8	201.6	201.6	204.6	204.6	200.9	200.9
	Oil	MJ	323.1	273.3	273.3	277.5	277.5	272.4	272.4
	Natural gas	MJ	2004.3	1624.7	1624.7	1643.9	1643.9	1613.3	1613.3
	Diesel	MJ	30.5	34.7	39.7	18.7	26.6	37.3	42.2
Emission to air	CO_2	kg	299.8	260.2	262.5	266.5	268.8	276.8	279.2
	NO_x	kg	2.762	2.764	2.806	2.369	2.411	2.844	2.886
	N_2O	kg	2.001	1.751	1.752	0.848	0.849	1.845	1.846
	CO	kg	0.165	0.204	0.247	0.204	0.247	0.208	0.250
	SO_x	kg	0.716	0.478	0.488	0.505	0.515	0.463	0.473
	CH_4	kg	0.208	0.212	0.216	0.256	0.260	0.242	0.246
	NH_3	g	0.126	-	-	39.08	39.08	-	-
water	NO_3-N	kg	0.459	0.455	0.456	0.359	0.360	0.481	0.482
	N to water	g	22.700	1.638	1.638	0.274	0.274	0.399	0.399
	P to water	mg	0.477	0.231	0.231	1.914	1.914	1.917	1.917
	15-15-15								
Resources	Phosphate rock	kg	59.9	60.1	60.1	63.7	63.7	63.7	63.7
	Potash salt	kg	139.9	83.5	83.5	83.5	83.5	83.5	83.5
	Hard coal	MJ	177.3	173.8	173.8	180.7	180.7	174.8	174.8
	Oil	MJ	240.3	239.1	239.1	245.1	245.1	237.0	237.0
	Natural gas	MJ	1671.0	1416.9	1416.9	1451.4	1451.4	1403.3	1403.3
	Diesel	MJ	55.8	48.8	53.8	44.2	49.1	60.4	65.3
Emission to air	CO_2	kg	218.5	267.7	270.0	310.3	312.6	299.5	301.8
	NO_x	kg	1.167	1.295	1.337	1.091	1.134	1.070	1.112
	N_2O	kg	1.557	0.817	0.818	0.358	0.359	1.306	1.307
	CO	kg	0.218	0.209	0.251	0.225	0.268	0.225	0.267
	SO_x	kg	0.952	0.980	0.990	1.424	1.434	0.937	0.947
	CH_4	kg	0.164	0.228	0.232	0.288	0.292	0.274	0.278
	NH_3	g	0.278	-	-	163.2	163.2	-	-
water	NO_3-N	kg	0.459	0.479	0.479	0.476	0.476	0.581	0.581
	N to water	g	23.700	4.100	4.100	0.546	0.546	0.652	0.652
	P to water	mg	0.825	0.786	0.786	6.900	6.900	6.900	6.900

Appendix Chapter 3:

Greenhouse gas emission during the production, transportation and application of mineral fertilizers, fertilizers applied via fertigation and fertilizer made from secondary raw materials in one cultivation period.

	N-content (%)	**Production**				**Transportation**		**Application**			
		CO_2 per kg fertilizer	N_2O per kg fertilizer	CO_2 per functional unit*	N_2O as CO_2-eq. per functional unit*	CO_2 per tkm	CO_2 per functional unit*	CO_2 per kg urea-N or nitrate N	CO_2 emission per functional unit*	N_2O emission per kg fertilizer	N_2O emission per functional unit*
AN[1]	35	1.26	0.00141	452	150	0.037	10.5	0.84	105	0.0054	581
AN + FG[2]	35	1.26	0.00141	452	150	0.037	10.5	0.84	105	0.0050	534
CAN[2]	27	0.98	0.00116	456	160	0.049	13.8	0.84	105	0.0042	581
CN + FG		0.98	0.00341	456	464	0.048	12.9	0.84	105	0.0028	379
UAN[4]	32	1.09	0.00070	426	82	0.041	11.6	0.94	333	0.0050	581
Urea	46	1.42	0.00004	386	3	0.027	7.9	1.6	446	0.0071	581
Urea + UI[5]	46	1.42	0.00004	386	3	0.027	7.9	1.6	446	0.0068	551
Urea + UI + NI[6]	46	1.42	0.00004	386	3	0.027	7.9	1.6	446	0.0045	364
Urea + FG	46	1.42	0.00004	386	3	0.027	7.9	1.6	446	0.0045	370
ASN[7]	26	0.93	0.00561	453	465	0.034	10.7	0.84	105	0.0041	461
ASN + NI	26	0.93	0.00561	453	465	0.034	10.7	0.84	105	0.0027	367
Feather meals	0.13	0.14	0.00140	255	734	0.015	25.8	0.84	105	0.0011	581
Meat-and-bone meals	0.10	0.68	0.00300	1088	1445	0.015	24.5	0.84	105	0.0012	581

Legu-minous crops meals	0.05	0.14	0.00001	850	7	0.008	53.8	0.84	105	0.0003	581

* representing an application of 125 kg N per hectare.

[1] Ammonium nitrate

[2]Fertigation

[3]Calcium ammonium nitrate

[4]Urea ammonium nitrate

[5]Urease inhibitor

[6]Nitrification inhibitor

Appendix Chapter 4:

Investigated drivers in the studied publications

Drivers	Publication
External precursors	
Involvement organizations/ co-operations	Abate et al., 2016; Ajayi, 2007; Alene et al., 2008; Handschuch and Wollni, 2016; Huang et al., 2015; Kutter et al., 2011; Lamba, 2009; Lambrecht et al., 2014; Magrini et al., 2016; Manda et al., 2015; Mapila et al., 2012; Ndiritu et al., 2014; Ogbonna et al., 2007; Robertson et al., 2012; Schreinemachers et al., 2007; Shiferaw et al., 2013; Stuart et al., 2015; Tey and Brindal, 2012; Tey et al., 2014; Wainaina et al., 2014; Wossen et al., 2015
Regulation	Ajayi et al., 2007; Busse et al., 2014; Chianu et al., 2012; Davidson et al., 2014; Eastwood et al., 2017; Gowing and Palmer, 2008; Handford et al., 2015; Hasler et al., 2016; Lamba, 2009; Magrini et al., 2016; Nikkilä et al., 2012; Sheahan et al., 2016; Stuart et al., 2015
Observability	Aubert et al., 2012; Batte and Arnold, 2003; Chianu et al., 2012; Gowing and Palmer, 2008; Haneklaus et al., 2002; Hayman et al., 2007; Herrera et al., 2016; Jochinke et al., 2007; Knowler and Bradshaw, 2007; Mahadevan and Asufu-Adjaye, 2015; Marra et al., 2003; Pandey, 1999; Rezaei-Moghaddam and Salehi, 2010; Robertson et al., 2012; Roxburgh et al., 2016; Shiferaw et al., 2013; Siddique et al., 2012; Simpson et al., 2014; Tey and Brindal, 2012; Zhang et al., 2016
Quality of support	Adesina and Baidu-Forson, 1995; Ajayi et al., 2007; Ajayi et al., 2011; Akudugu et al., 2012; Aubert et al., 2012; Batte and Arnold, 2003; Busse et al., 2014; Chianu and Tsujii, 2004; Daberkow and McBride, 2003; Davidson et al., 2014; Eastwood et al., 2017; Gowing and Palmer, 2008; Hasler et al., 2016; Hayman et al., 2007; Herrera et al., 2016; Huang et al., 2015; Jochinke et al., 2007; Ju et al., 2016; Knowler and Bradshaw, 2007; Kopainsky et al., 2012; Kutter et al., 2011; Lamba, 2009; Lambrecht et al., 2014; Mafongoya et al., 2006; Magrini et al., 2016; Mahadevan and Asufu-Adjaye, 2015; Mapila et al., 2012; Namara et al., 2007; Nikkilä et al., 2012; Ogbonna et al., 2007; Reichardt et al., 2009; Robertson et al., 2012; Roxburgh et al., 2016; Siddique et al., 2012; Watcharaanantapong et al., 2014; Weber and McCann, 2014; Zhang et al., 2016; Zhao et al., 2016
Information	Ajayi et al., 2007; Aubert et al., 2012; Busse et al., 2014; Chang and Tsai, 2015; Chianu et al., 2012; Daberkow and McBride, 2003; Davidson et al., 2014; Eastwood et al., 2017; Giller et al., 2011; Handford et al., 2015; Hasler et al., 2016; Hayman et al., 2007; Herrera et al., 2016; Jochinke et al., 2007; Ju et al., 2016; Kamau et al., 2014; Knowler and Bradshaw, 2007; Kopainsky et al., 2012; Kutter et al., 2011; Lamba, 2009; Lambrecht et al., 2014; Mafongoya et al., 2006; Magrini et al., 2016; Manda et al., 2015; Mapila et al., 2012; Marra et al., 2003; Moreau et al., 2013; Namara et al., 2007; Nikkilä et al., 2012; Pandey, 1999; Reichardt et al., 2009; Robertson et al., 2012; Schreinemachers et al., 2007; Shiferaw et al., 2013; Siddique et al., 2012; Smale and Heise, 1993; Stricklander et al., 1998; Stuart et al., 2015; Swinton and Lowenberg-

	Deborer, 2001; Tey and Brindal, 2012; Tey et al., 2014; Wainaina et al., 2014; Watcharaanantapong et al., 2014; Weber and McCann, 2014; Zhao et al., 2016
Compatibility	Aubert et al., 2012; Batte and Arnold, 2003; Eastwood et al., 2017; Haneklaus et al., 2002; Hayman et al., 2007; Jochinke et al., 2007; Kanellolpoulos et al., 2012; Knowler and Bradshaw, 2007; Reichardt et al., 2009; Robertson et al., 2012; Tey et al., 2014
Factors suggested by other theories	
Expectation	Adrian et al., 2005; Akudugu et al., 2012; Aubert et al., 2012; Batte and Arnold, 2003; Busse et al., 2014; Handford et al., 2015; Haneklaus et al., 2002; Hayman et al., 2007; Marra et al., 2003; Stuart et al., 2015; Tey and Brindal, 2012; Tey et al., 2014; Zhang et al., 2016
Task-technology fit	Adrian et al., 2005; Aubert et al., 2012; Batte and Arnold, 2003; Busse et al., 2014; Chianu et al., 2012; Daberkow and McBride, 2003; Eastwood et al., 2017; Hayman et al., 2007; Jochinke et al., 2007; Knowler and Bradshaw, 2007; Manda et al., 2015; Reichardt et al., 2009; Rezaei-Moghaddam and Salehi, 2010; Robertson et al., 2012; Stricklander et al., 1998; Stuart et al., 2015; Tey and Brindal, 2012; Watcharaanantapong et al., 2014; Zhang et al., 2016
Access to credit	Abate et al., 2016; Ajayi et al., 2011; Ajayi, 2007; Akudugu et al., 2012; Alene et al., 2008; Asfaw and Admassie, 2004; Chauhan et al., 2012; Chianu and Tsujii, 2004; Chianu et al., 2012; Daberkow and McBride, 2003; Emerick et al., 2015; Katungi et al., 2011; Lambrecht et al., 2014; Lamers et al., 2015a; Mahadevan and Asufu-Adjaye, 2015; Namara et al., 2007; Ndiritu et al., 2014; Ogbonna et al., 2007; Oladoja et al., 2009; Pandey, 1999; Schreinemachers et al., 2007; Shiferaw et al., 2013; Siddique et al., 2012; Smale and Heise, 1993; Swinton and Lowenberg-Deborer, 2001; Tey et al., 2014; Wainaina et al., 2014; Wossen et al., 2015
Market access	Ajayi et al., 2007; Ajayi, 2007; Alene et al., 2008; Chianu and Tsujii, 2004; Chianu et al., 2012; Ciceri et al., 2015; Daberkow and McBride, 2003; Doss and Morris, 2001; Eastwood et al., 2017; Gowing and Palmer, 2008; Kamau et al., 2014; Katungi et al., 2011; Lambrecht et al., 2014; Magrini et al., 2016; Mahadevan and Asufu-Adjaye, 2015; Manda et al., 2015; Mapila et al., 2012; Namara et al., 2007; Ndiritu et al., 2014; Nin-Pratt and McBride, 2014; Pandey, 1999; Rerkasem, 2005; Sheahan et al., 2016; Shiferaw et al., 2013; Siddique et al., 2012; Simpson et al., 2013; Simpson et al., 2014; Stuart et al., 2015; Tey and Brindal, 2012; Wainaina et al., 2014
Contextual factors	
Gender	Abate et al., 2016; Ajayi et al., 2011; Ajayi, 2007; Akudugu et al., 2012; Alene et al., 2008; Asfaw and Admassie, 2004; Chauhan et al., 2012; Chianu et al., 2012; Dalton et al., 2011; Doss and Morris, 2001; Handford et al., 2015; Handschuch and Wollni, 2016; Kamau et al., 2014; Knowler and Bradshaw, 2007; Manda et al., 2015; Mapila et al., 2012; Mudhara et al., 2003; Ndiritu et al., 2014; Oladoja et al., 2009; Schreinemachers et al., 2007; Sheahan et al., 2016; Tey et al., 2014; Wainaina et al., 2014

Age	Abate et al., 2016; Adesina and Baidu-Forson, 1995; Akudugu et al., 2012; Alene et al., 2008; Aubert et al., 2012; Busse et al., 2014; Chianu and Tsujii, 2004; Daberkow and McBride, 2003; Doss and Morris, 2001; Handford et al., 2015; Handschuch and Wollni, 2016; Katungi et al., 2011; Knowler and Bradshaw, 2007; Kutter et al., 2011; Lamba, 2009; Lambrecht et al., 2014; Mahadevan and Asufu-Adjaye, 2015; Manda et al., 2015; Ndiritu et al., 2014; Ogbonna et al., 2007; Oladoja et al., 2009; Reichardt et al., 2009; Robertson et al., 2012; Schreinemachers et al., 2007; Sheahan et al., 2016; Tey and Brindal 2012; Tey et al., 2014; Wainaina et al., 2014; Watcharaanantapong et al., 2014; Wossen et al., 2015; Zhang et al., 2016
Education	Adrian et al., 2005; Akudugu et al., 2012; Alene et al., 2008; Asfaw and Admassie, 2004; Aubert et al., 2012; Busse et al., 2014; Chianu and Tsujii, 2004; Davidson et al., 2014; Doss and Morris, 2001; Giller et al., 2011; Handschuch and Wollni, 2016; Katungi et al., 2011; Knowler and Bradshaw, 2007; Kutter et al., 2011; Lamba, 2009; Lambrecht et al., 2014; Mahadevan and Asufu-Adjaye, 2015; Manda et al., 2015; Marra et al., 2003; Ndiritu et al., 2014; Ogbonna et al., 2007; Oladoja et al., 2009; Reichardt et al., 2009; Rezaei-Moghaddam and Salehi, 2010; Robertson et al., 2012; Shiferaw et al., 2013; Siddique et al., 2012; Swinton and Lowenberg-Deborer, 2001; Tey and Brindal, 2012; Tey et al., 2014; Wainaina et al., 2014; Watcharaanantapong et al., 2014; Weber and McCann, 2014; Wossen et al., 2015; Zhang et al., 2016
Farm size	Adesina and Baidu-Forson, 1995; Adrian et al., 2005; Akudugu et al., 2012; Aubert et al., 2012; Chauhan et al., 2012; Daberkow and McBride, 2003; Dalton et al., 2011; Handschuch and Wollni, 2016; Ju et al., 2016; Kamau et al., 2014; Knowler and Bradshaw, 2007; Kutter et al., 2011; Lambrecht et al., 2014; Mahadevan and Asufu-Adjaye, 2015; Manda et al., 2015; Mapila et al., 2012; Marra et al., 2003; Mudhara et al., 2003; Namara et al., 2007; Ndiritu et al., 2014; Oduol and Tsuji, 2005; Reichardt et al., 2009; Robertson et al., 2012; Roxburgh et al., 2016; Schreinemachers et al., 2007; Shiferaw et al., 2013; Sirrine et al., 2010; Smale and Heise, 1993; Takăcs-György, 2007; Tey and Brindal, 2012; Tey et al., 2014; van Rees et al., 2014; Wainaina et al., 2014; Watcharaanantapong et al., 2014; Weber and McCann, 2014; Wossen et al., 2015; Zhang et al., 2016
Land ownership	Emerick et al., 2015; Kamau et al., 2014; Katungi et al., 2011; Knowler and Bradshaw, 2007; Lamba, 2009; Lamers et al., 2015b; Mahadevan and Asufu-Adjaye, 2015; Manda et al., 2015; Mapila et al., 2012; Nin-Pratt and McBride, 2014; Oduol and Tsuji, 2005; Ogbonna et al., 2007; Pandey, 1999; Schreinemachers et al., 2007; Tey and Brindal 2012; Wainaina et al., 2014; Watcharaanantapong et al., 2014; Wossen et al., 2015

Appendix Chapter 5:

Pairwise spearman rank correlation coefficient between variables (questions) without group effects; significant differences ($p \leq 0.05$) are marked with a star.

	1	**2**	**3**	**4**
More frequently extreme weather scenarios (**1**)				
Fertilization has to be adapted to weather scenarios (**2**)	0.33*			
Further restriction of N and P use (**3**)	0.12	0.34*		
First user of new technologies (**4**)	-0.22	0.09	0.24	
New technologies are better	0.16	0.27	0.19	0.34*

To avoid spurious correlation we decide to split the question into the groups (producer, trader, farmer):

Pairwise spearman rank correlation coefficient for producers; significant differences ($p \leq 0.05$) are marked with a star.

	1	**2**	**3**	**4**
More frequently extreme weather scenarios (**1**)				
Fertilization has to be adapted to weather scenarios (**2**)	0.98*			
Further restriction of N and P use (**3**)	0.39	0.44		
First user of new technologies (**4**)	0.01	0.08	0.90*	
New technologies are better	0.61	0.72*	0.32	0.03

Pairwise spearman rank correlation coefficient for traders; significant differences ($p \leq 0.05$) are marked with a star.

	1	**2**	**3**	**4**
More frequently extreme weather scenarios (**1**)				
Fertilization has to be adapted to weather scenarios (**2**)	0.08			
Further restriction of N and P use (**3**)	0.13	0.58*		
First user of new technologies (**4**)	-0.30	-0.06	0.05	
New technologies are better	0.10	0.11	0.12	0.30

Pairwise spearman rank correlation coefficient for farmers.

	1	**2**	**3**	**4**
More frequently extreme weather scenarios (**1**)				
Fertilization has to be adapted to weather scenarios (**2**)	0.29			
Further restriction of N and P use (**3**)	-0.39	-0.20		
First user of new technologies (**4**)	-0.27	0.47	0.10	
New technologies are better	-0.21	0.14	0.43	0.45

About the author

Kathrin Hasler was born on October 17, 1985 in Reutlingen, Germany. She attended Leibniz University Hannover from 2005 to 2007 and graduated with B.Sc. She focused her studies on plant production and economics, with her bachelor-thesis about eco-labeling in the cut-flower sector. In 2010 she finished her M.Sc. at the University Kiel with main aspects in plant nutrient and plant production writing her master-thesis about glucosinolates and its degradation products in Chinese cabbage. In 2011 she started working for the University of Applied Science in Osnabrück in the field of plant nutrient and supply chain management within the project supply chain and environmental management of three different fertilizer product types. Stemming from this position the possibility of an external PhD candidate in the Management Studies Group at Wageningen University (since 2012) in cooperation with the University of Bonn was generated. In 2016 she received a fellowship from the University of Applied Science in Osnabrück to finish her PhD studies. Since 2016 she is a visiting scientist at Kiel University.

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