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Costs and benefits of ammonia and particulate matter emission abatement and interactions with greenhouse gas emissions in German agriculture

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List of Abbreviations

%	Percentage
€	Euro
A	Annum
ap	Animal place
BAU	Business-as-usual
BF	Balanced fertilisation
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact (model)
CCE	Coordination Centre for Effects
CGE	Computable General Equilibrium (model type)
CH_4	Methane
CLRTAP	Convention on Long-range Transboundary Air Pollution
cm	Centimetre
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CORINE	Coordination of Information on the Environment
CRC	Colorectal cancer
CVD	Cardio-vascular disease
DALY	Disability-adjusted life years
DESTATIS	Statistisches Bundesamt
dm	Dry matter
e.g.	Exempli gratia
EDGAR	Emission Database for Global Atmospheric Research
EFEM	Economic Farm Emission Model
EMEP	European Monitoring and Evaluation Programme
EU	European Union
EUR	Euro
FADN	Farm accountancy data network
FAKT	Förderprogramm für Agrarumwelt, Klimaschutz und Tierwohl
FAO	Food and Agriculture Organization
F-gases	Fluorinated greenhouse gases

g	Gram
GAINS	Greenhouse Gas - Air Pollution Interactions and Synergies (model)
Gg	Gigagram
GHG	Greenhouse gas
GJ	Gigajoule
ha	Hectare
i.e.	Id est
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km^2	Square kilometre
kWh	Kilowatt hour
LU	Livestock unit
m^3	Cubic metre
Mg	Megagram
MJ	Megajoule
N	Nitrogen
n.c.	Not calculated
n/a	Not applicable
N_2O	Nitrous oxide, laughing gas
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
NO_3	Nitrate
NO_x	Nitrogen oxides
NUTS	Nomenclature des unités territoriales statistiques
PDF	Potentially disappeard fraction
PE	Partial equilibrium (model type)
PM	Particulate matter
PM_{10}	Particulate matter with an aerodynamic diameter of less than 10 µg
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of less than 2.5 µg
RAINS	Regional Air Pollution Information and Simulation
RMDI	Recommended maximum dietary intake
SC	Soil carbon

SEDAC	Socioeconomic Data and Application Center
SO_2	Sulphur dioxide
SOC	Soil organic carbon
TAN	Total ammoniacal nitrogen
Tg	Teragram
Yr	Year
UNECE	United Nations Economic Commission for Europe
WHO	World Health Organization
YOLL	Years of Life Lost
μm	Micrometre

1 General Introduction

1.1 Background

In the past decades, agricultural and particularly livestock production have increased with population growth and increasing demand for food, especially for livestock products, at global level. This trend is expected to continue in the coming decades and may even be fortified by an increasing demand for non-food biomass in an economy based on renewable biological resources (Bruinsma, 2009; FAO, 2006; Kearney, 2010; Tilman et al., 2002; European Commission, 2012).

Agriculture determines not only the level of food production, but also, to a large degree, the state of the environment. Livestock production accounts for 70% of all agricultural land globally and has been associated with expansion into natural ecosystems, adversely affecting biodiversity, and greenhouse gas emissions and the carbon cycle (Godfray et al., 2010; Steinfeld et al., 2006; Thornton, 2010). Besides these environmental effects, agriculture also adds detrimental amounts of nitrogen to ecosystems (Bouwman et al., 2013). Nitrogen pollution, primarily via emissions of ammonia (NH_3), is considered to be among the top three threats to global biodiversity. Much of the emissions of NH_3 is transported by air and deposited in nitrogen-limited terrestrial ecosystems where it leads to unintentional fertilisation and loss of terrestrial biodiversity (Dise et al., 2011; Erisman et al., 2008; Townsend and Howarth, 2010). In the atmosphere, parts of NH_3 are converted into ammonium aerosols that are a fraction of secondary fine particulate matter ($PM_{2.5}$) (Krupa, 2003). Thereby, NH_3 emissions pose also a threat to air quality (Moldanová et al., 2011). Emissions of $PM_{2.5}$, both primary and secondary, may lead to respiratory and cardiovascular diseases and a reduction in life expectancy (Brunekreef and Holgate, 2002; World Health Organization Regional Office for Europe, 2013). Additionally, NH_3 can lead to the emissions of the greenhouse gas nitrous oxide and indirectly affect the climate (Krupa, 2003).

The adverse impacts of agricultural production on the environment and on public health are costs that are typically not measured and often do not influence farmers' or society's choices about production methods or food products. These external costs question the sustainability of current agricultural production. Sustainable agricultural production would consider all costs and benefits and maximise the net benefits for society. "If society is to maximize the net benefits of agriculture, there must be a fuller accounting of both the costs and the benefits of alternative agricultural practices, and such an accounting must become the basis of policy, ethics and action" (Tilman et al., 2002).

At the international policy level, the need to abate NH_3 and PM emissions has been recognised, and policies to halt the loss of biodiversity and to improve air quality and the sustainability of agricultural production (e.g., included in the Common Agricultural Policy reform 2014-2020) have been introduced (European Communities, 2001, 2006, 2008; European Union, 2010; UNECE, 2013). Targets for the mitigation of greenhouse gas emissions for the year 2020 are set in the European Union's "20-20-20" climate and energy package and are further developed in the 2030 climate and energy framework (European Commission, 2008, 2013). If the net benefits should become a basis for policy and action, as suggested by Tilman et al. (2002), the question needs to be raised what the damage costs of environmental impacts from agriculture account for and what the net benefits for the society would be if these damages were avoided.

Germany faces a situation similar to the aforementioned. Agricultural production, and mainly livestock production, has increased in the last decades. Livestock production covers now 65% of agricultural area in Germany. The consumption of livestock products has increased in the past decades and is now about twice as high as recommended in healthy eating guidelines (BMELV, 2010; Max Rubner-Institut, 2008). With 545 Gigagram (Gg) of NH_3 emissions in 2012, Germany is among the countries with the highest NH_3 emissions in the European Union (EU) both at national level and per unit utilised agricultural area, and a large share of its natural and semi-natural ecosystems is under pressure from nitrogen deposition (Builtjes et al., 2011; UNECE, 2013; Eurostat, 2012). 94% of these NH_3 emissions originated from agriculture; thereof about 85% from livestock production. Besides NH_3, agriculture contributes to the emissions of primary PM and of greenhouse gases (Table 1-1) (Umweltbundesamt, 2013, 2014).

Table 1-1: Emissions of ammonia and particulate matter (PM_{10} and $PM_{2.5}$) from livestock production, crop production and the whole national society in Germany in 2012 (in Gg)

	NH_3	PM_{10}	$PM_{2.5}$	Greenhouse gases
Livestock production	437	20	5	$29*10^3$
Crop production	75	19	1	$41*10^3$
National total	545	217	112	$940*10^3$

Source: Umweltbundesamt (2013, 2014)

Germany is committed to comply with the international policy reduction targets for NH_3 and PM emissions as well as for the emissions of greenhouse gases. The agricultural sector can contribute a large share to these reductions and may, by reducing NH_3 emissions, even offer a cost-effective means for PM emission abatement (Pinder et al., 2007). As NH_3 and PM emissions partly originate from the same agricultural activities, interactions between NH_3 and PM emission abatement and greenhouse gas emissions in the sense that NH_3 and PM emission abatement measures may affect greenhouse gas emissions can exist. There is a need to analyse the options for air pollutant emission abatement in agriculture in Germany considering effects on greenhouse gases and to estimate the costs for farmers and the benefits for the society and thereby identify those measures that offer the largest net benefits.

1.2 Emission abatement and abatement costs

In general, emissions are determined by the production activity from which they originate, e.g. the livestock type (cattle, pigs) or the manure system (e.g. straw-based or slurry-based). Obviously, they are also determined by the quantity of a production activity, e.g. the number of animals of a particular type that are present in a year. The general equation is emissions estimation equals the activity times the emission factor, i.e., the emission per unit of activity (European Environment Agency, 2013). The emissions of production activities can be reduced by a range of technical measures that capture the emissions at their sources before they enter the atmosphere. These measures reduce the emission factor but do not alter the quantity of production. Besides technical measures, behavioural changes can reduce anthropogenic driving forces that generate emissions (Amann et al., 2011). Thus, reductions in production activities or a shift to products that are less detrimental to the environment can reduce emissions. On a food product base, plant-based food products have lower nitrogen and greenhouse gas emissions than livestock products (Carlsson-Kanyama and González, 2009; Leip et al., 2014). These findings suggest that, besides technical measures, a shift in human diets from livestock products to plant-based food products can also contribute to the abatement of atmospheric emissions.

1.2.1 Technical abatement measures

Technical NH_3 emission abatement measures in agriculture have mainly been analysed in the framework of air quality policy assessment regarding their abatement potentials, costs and cost-effectiveness (Döhler et al., 2011; Wagner et al., 2012; Webb et al., 2006; Bittman et al., 2014). PM abatement measures and related technical costs in livestock housing are described in Grimm (2008). Evidence exists that PM emissions in crop production vary according to soil characteristics, soil cultivation methods, e.g. ploughing or harrowing, and harvesting activities (Funk et al., 2008; Hinz and Hoek, 2007; Öttl and Funk, 2007). Yet assessments of PM emission abatement measures in agriculture are lacking. Measures for reducing greenhouse gas emissions in livestock and in crop production including land use effects and carbon sequestration have been reviewed and analysed regarding their reduction potentials in Bellarby et al. (2013), Garnett (2011) and, including mitigation costs, in MacLeod et al. (2010).

These previously mentioned studies referred to emissions of either NH_3 or PM emissions or of greenhouse gases and neglected possible interactions among air pollutants and greenhouse gases. More integrative cost-effectiveness studies addressed agricultural measures that reduce nitrogen (N) gases and found synergies of air pollutant and greenhouse gas reduction via the abatement of N compounds (Oenema et al. 2009; Amann et al. 1999). Additional studies indicated that interactions between NH_3 emission abatement and greenhouse gas mitigation in agriculture exist and that simultaneous reductions can lower overall reduction costs (Brink et al. 2005; Eory et al. 2013). However, these approaches have their limitations in assessing abatement measures that affect multiple pollutants with different environmental effects.

1.2.2 Diet shifts

Human diets have mainly been assessed regarding their impacts on the climate. Lower consumption of animal-based food, particularly of ruminant meat, reduces greenhouse gases partly to a larger extend than technical measures (Audsley et al., 2010; Bellarby et al., 2013; Amann et al., 1999; McMichael et al., 2007; Popp et al., 2010; Stehfest et al., 2009). Furthermore, diets with low livestock product consumption need less land compared to diets with high livestock product consumption (Gerbens-Leenes and Nonhebel, 2002; Eory et al., 2013; Amann et al., 2011). Integrative studies showed that diets rich in plant products simultaneously benefit the climate, the supply of land, water and energy, biodiversity conservation and human health relative to diets rich in animal products (Aiking, 2011; Boer et al., 2006; Tukker et al., 2011). A reduction in livestock product consumption may also reduce dietary health risks such as colon cancer and saturated fat related heart diseases (Amann et al., 1999; Friel et al., 2011; McMichael et al., 2007). There is a need to analyse the impacts of a diet shift on NH_3 and PM emissions and effects on greenhouse gases and associated impacts on the environment and on human health.

1.3 Benefits of emission abatement

Many studies have assessed the costs of abatement measures, but did not estimate the damage costs of air pollution and the quantity of damage costs avoided by emission abatements, i.e. what the benefits for the society in terms of avoided damage costs would be. From an economic welfare perspective and to internalise such external costs, avoided damage costs need to be estimated. External health damage costs of NH_3 emissions were estimated for Denmark and of NH_3 and $PM_{2.5}$ emission abatement in the assessment of air quality policies in the EU (e.g., Brandt et al., 2013; Holland, 2012, 2014; Pye et al., 2008; Brink and Grinsven, 2011). Grinsven et al. (2013) estimated the benefits of reducing nitrogen pollution in Europe. Within the assessment of EU air quality policies, impacts on biodiversity were assessed with a critical loads approach. This approach is not suitable for monetary valuation. However, it has been recognized that impacts on biodiversity should be expressed in monetary terms and included in the benefit analysis (European Communities, 2005). An overview of damage costs of climate change that have been estimated in various studies is given in Umweltbundesamt (2007). The benefit estimates allow for the assessment of emission abatement measures that affect multiple pollutants where the application of cost-effectiveness analysis is limited. Moreover, a cost-benefit analysis can help to identify abatement measures that increase welfare most.

1.4 Objectives and research questions

The general objective of my thesis research was to increase the understanding of the full effects of NH_3 and PM emission abatement measures in agriculture. In particular, the objective was to quantify costs and benefits of reducing NH_3 and PM emissions in agriculture in Germany considering interactions with greenhouse gases and to identify cost-efficient NH_3 and PM emission abatement measures. To achieve this objective, the following key research questions were addressed:

1. Is a cost-benefit approach appropriate for assessing NH_3 and PM emission abatement measures and related impacts on human health and on biodiversity, particularly when expecting interactions between NH_3 and PM emission abatement with greenhouse gas emissions?
2. What are the abatement potentials, the abatement costs for farmers and the benefits for the society of technical NH_3 and PM emission abatement measures and of a shift in diets?
3. Do interactions among the abatement of NH_3 and PM emissions and greenhouse gas emissions exist, and do they influence the abatement costs and the benefits?

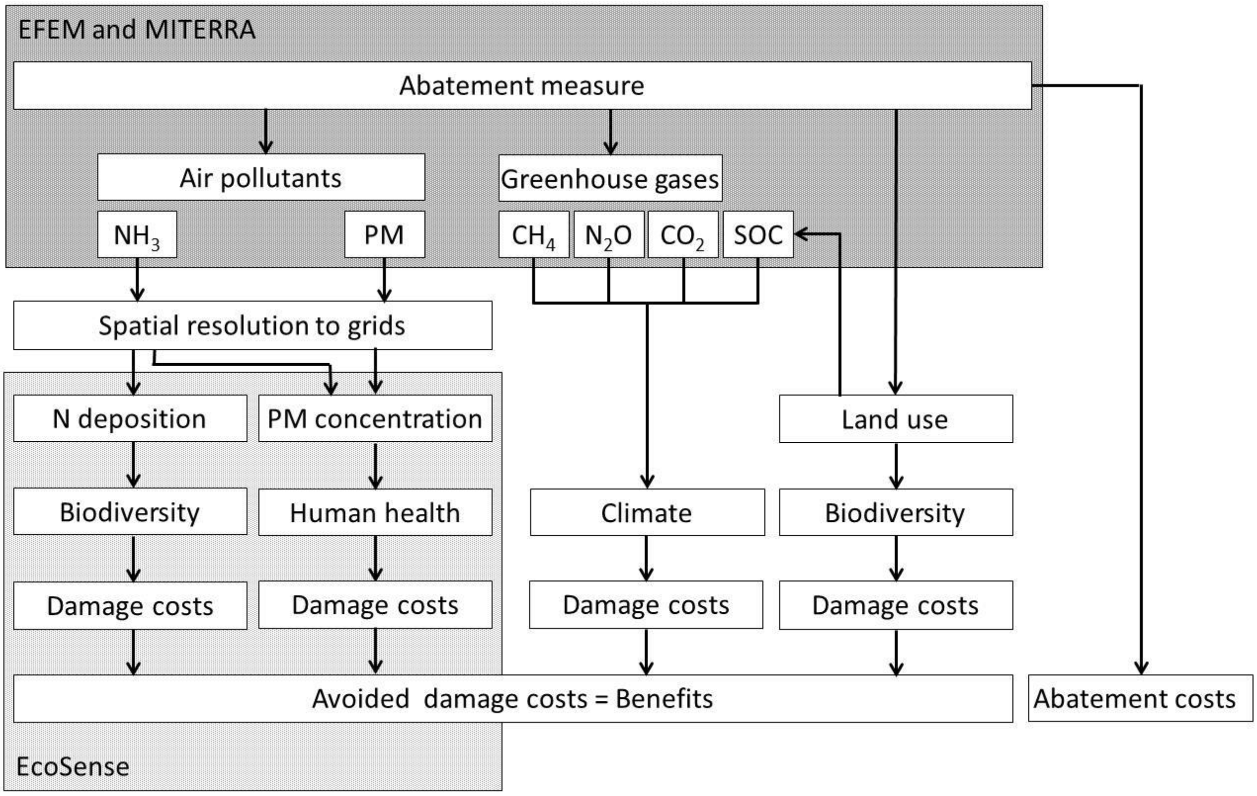
To answer these questions, the general objective has been disaggregated into the following specific research objectives and tasks:

- To set up and apply a conceptual framework for the evaluation of NH_3 and PM emission abatement measures in agriculture regarding their costs and benefits;
- To include PM emissions from agriculture in the assessment and the modelling framework;
- To analyse interactions of NH_3 and PM emission abatement measures and greenhouse gas emissions in agriculture;
- To quantify the abatement potentials, the abatement costs and the benefits for human health and for biodiversity of NH_3 and PM emission abatement measures in agriculture complemented by benefits of greenhouse gas reductions;
- To analyse and compare technical abatement measures and a diet shift regarding their abatement potentials, abatement costs and benefits.

1.5 Description of the method

This modelling approach developed and applied in my thesis research combines agricultural emission modelling and integrated environmental impact assessment. The NH_3 and PM emission abatement measures were evaluated regarding their abatement costs for farmers and their benefits to society in a cost-benefit-analysis (Figure 1-1). The assessment included interactions with greenhouse gases and impacts of land use change. The benefits comprise monetised impacts on terrestrial biodiversity, on human health (morbidity and mortality) and the climate. This thesis research brings together different methods that estimate environmental and health impacts and that valuate these impacts in monetary terms. This is a precondition for comparing different impacts and for aggregating them in one value, the damage costs. This approach enables to assess multiple effects of emission abatement measures such as the interactions among NH_3 and PM emission abatement and greenhouse gas mitigation and to compare avoided damage costs to abatement costs.

The reference emissions of NH_3, PM and greenhouse gases, including soil carbon sequestration, and the abatement potentials and costs of technical measures were taken from a study carried out with the economic-ecological farm model EFEM by Beletskaya (2016) (chapter 2 and chapter 3). The reference emissions and the abatement potentials of a diet shift were estimated with the biophysical model MITERRA (Lesschen et al., 2009; Velthof et al., 2009) (chapter 4 and chapter 5).



SOC = soil organic carbon

Figure 1-1: Evaluation of abatement measures for NH_3 and PM emissions and interactions with greenhouse gas emissions as developed and applied in this thesis research

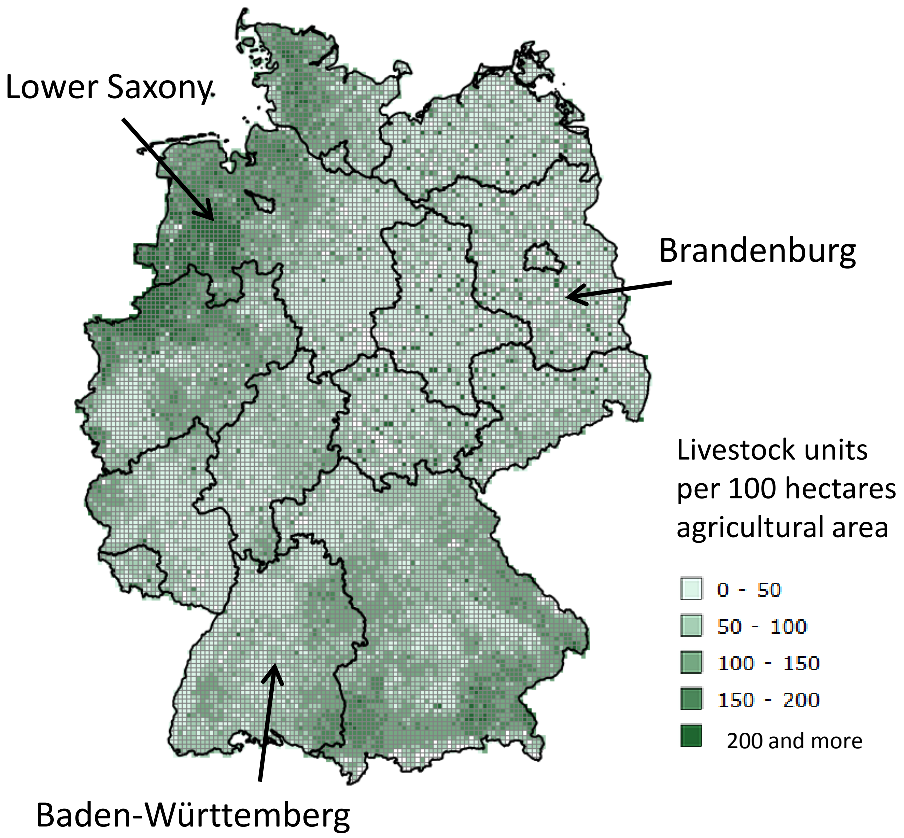
The farm model EFEM is a static linear supply model that maximises the gross margins of farms (Neufeldt, Schäfer 2008). Production factors, prices and production capacities in the model are exogenous. The model is based on typical farms that were derived from analyses of datasets of the Farm Accountancy Data Network and classified into farm types following the EU classification system. Their production capacities define the scope of the linear optimisation process. The results at farm level are extrapolated to regional level with linear extrapolation. Thus, the analysis at regional level is based on a bottom-up approach. The core of EFEM is the production module that depicts crop and livestock production activities considering their regional differences in yields, intensities, performance and costs. The production module also estimates emissions that originate from production activities and includes abatement measures. For NH_3 emissions in livestock production, it distinguishes the emission sources feeding, housing, manure storage, manure application and fertiliser application and traces the NH_3 emissions along these stages. The analysis of NH_3 emission abatement measures comprises interactions along the emission stages, because reductions at earlier stages have impacts on the N content of manure and on NH_3 emission potentials in subsequent stages. The module includes also PM emissions and greenhouse gas emissions of agricultural and upstream processes. Hence, their balance contains emissions of agricultural production processes on the farms and of the production of farm inputs such as purchased feed, fertilisers and plant protection product. The changes in gross margins reflect the farmers' abatement costs of implementing emission abatement measures.

The model MITERRA calculates annual nutrient flows and greenhouse gas emissions from agriculture at NUTS-2 and NUTS-1 levels in the EU. Main input data are crop areas, livestock distribution, feed inputs (derived from the CAPRI model), animal numbers, excretion factors, NH_3 emission factors (derived from the GAINS model), crop yields, fertiliser consumption, animal production (from FAO statistics) and emissions factors for greenhouse gases (from IPCC). Like EFEM, MITERRA distinguishes the livestock emission sources feeding, housing, manure storage and manure application and includes greenhouse gas emissions from fertiliser production. To calculate emissions of $PM_{2.5}$, I implemented $PM_{2.5}$ emission factors for different livestock types, arable land and fuel use in MITERRA. The model analysis of environmental impacts was complemented by estimates of economic impacts on the farmers based on data from the literature.

In this thesis research, the impacts and benefits of NH_3 and PM emission abatement were estimated with the environmental impact assessment model EcoSense, applying the impact-pathway-approach in combination with a monetary valuation (Bickel, Friedrich 2005). This approach tracks emissions along the complete chain of causal relations starting from their source and subsequent dispersion and conversion in the atmosphere to their impacts on various receptors (e.g. human population, ecosystems). The atmospheric dispersion modelling in EcoSense simulated the transport of NH_3 and PM emissions in the atmosphere and the formation of secondary particles and resulted in PM concentration and N deposition. Physical impacts of changes in PM concentration on human health and of changes in N deposition on terrestrial ecosystems and biodiversity were estimated. These were weighed with monetary values and aggregated into one value, the damage costs. The approach is presented in chapter 2. The damage costs of impacts of greenhouse gas emissions and climate change were based on literature reviews. Avoided damage costs, representing the benefits of air pollutant and greenhouse gas reduction, were compared to farmers' abatement costs, and the net benefits and benefit-to-cost ratios were estimated. Only abatement measures whose benefits exceed the costs, i.e. with positive net benefits or a benefit-to-cost ratio larger than one, should be implemented.

The technical abatement measures that were analysed were substitution of urea fertiliser, reduced tillage, low-protein feeding of pigs and poultry, manure storage cover techniques, manure application techniques and exhaust air purification systems. As a diet shift, a 50% reduction in livestock product consumption and production, compensated by plant-based food consumption and production, was analysed in combination with three scenarios of alternative use of land freed up from livestock feed production: *food supply* with increased cereal production for export, *biomass* with perennial lignocellulosic crop cultivation for non-food use and *biodiversity* with extensive grassland production and fallows on arable land.

The technical measures were analysed in three case studies in the German Federal States of Baden-Württemberg, Brandenburg and Lower Saxony (Figure 1-2). Baden-Württemberg, in the south-west of Germany, has 1.4 million hectares (ha) of agricultural area and a livestock density of 0.7 livestock units per ha and pictures a region with a large share of forage-growing farms and mixed farms at small scale. Brandenburg (north-east Germany) has 1.3 million ha of agricultural area and 0.4 livestock units per ha and represents a region with large specialised crop production farms with large fields and sandy soils. It was considered suitable for the analysis of PM emission reduction measures in crop production. Lower Saxony, in north-west Germany, has 2.6 million ha of agricultural area and 1.2 livestock units per ha and depicts a region with intensive livestock husbandry and high shares of both NH_3 and PM emissions. The shifts in diets were analysed at the EU level and at the national level of Germany.



Source: Statistische Ämter des Bundes und der Länder

Figure 1-2: Livestock units per 100 hectares utilised agricultural area in the year 2010 in Germany (grid of 5 kilometres)

1.6 Outline

After the general introduction, this thesis presents the four research chapters and ends with the synthesis that integrates the research chapters.

Chapter 2 presents the conceptual framework for evaluating NH_3 and PM emission abatement measures in agriculture. In this chapter, the modelling approach that estimated farmers' abatement potentials and costs and society's benefits is described and applied to examples of technical NH_3 emission abatement measures in livestock production in Lower Saxony.

Chapter 3 evaluates technical abatement measures of NH_3, PM_{10} and $PM_{2.5}$ emissions in livestock and crop production considering their interactions with greenhouse gas emissions. Abatement potentials, costs for farmers and benefits for the society of human health, biodiversity and the climate are estimated. The effects of interactions on net benefits, average abatement costs and cost-efficiency are detailed.

Chapter 4 analyses the impacts of a diet shift on human health, on land use and on NH_3 and greenhouse gas emissions in the EU. The health effects include those related to the dietary change. The study indicates that animal-based food consumption in Germany is above the EU average and intake of proteins, red meat and saturated fat exceeds dietary recommendations providing scope for diet shifts in Germany.

Chapter 5 builds on the study presented in chapter 4 and investigates the impacts of a diet shift on the emissions of NH_3, $PM_{2.5}$ and greenhouse gases in Germany. In the presence of competing land use, the analysis comprises scenarios for the alternative use of land freed up from livestock production and their impacts on food supply, non-food biomass supply and biodiversity. The impacts are assessed according to their costs for farmers and the benefits for the society of human health, biodiversity and the climate.

Chapter 6, the synthesis, integrates and discusses the results of the previous research chapters. It describes the main findings of the thesis and compares the technical abatement measures and the diet shift. Options to reduce emissions in agriculture and related environmental impacts in a cost-efficient way are proposed. The implications for science, society, policy and future research are discussed.

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2 Assessing ammonia emission abatement measures in agriculture: Farmers’ costs and society’s benefits – a case study for Lower Saxony, Germany

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This chapter was submitted as Susanne Wagner, Elisabeth Angenendt, Olga Beletskaya, Jürgen Zeddies: Assessing ammonia emission abatement measures in agriculture: Farmers’ costs and society’s benefits – a case study for Lower Saxony, Germany. Agricultural Systems (under review).

Abstract

Ammonia (NH_3) emissions have adverse impacts on the environment and, being a precursor for fine particulate matter, also on human health. About 95% of NH_3 emissions originate from agriculture, mainly from livestock husbandry. This case study is aimed at presenting an approach that evaluates NH_3 emission abatement measures in agriculture regarding their abatement costs for farmers and their benefits for the society in terms of avoided external costs of health damages and loss of terrestrial biodiversity. Following the impact-pathway chain, a bioeconomic farm model for estimating NH_3 emission reductions and abatement costs was combined with an environmental impact assessment model for estimating the benefits for human health and biodiversity. The case study analysed a variety of manure storage cover and application techniques in Lower Saxony, a region in the north-west of Germany with the highest livestock density in Germany and high NH_3 emissions. In the reference situation, the damage costs of NH_3 emissions were EUR 2.7 billion. The implementation of concrete storage covers and slurry injection, the most effective measures, reduced NH_3 emissions by 25% and achieved net benefits of EUR 505 million. Farmers' average abatement costs ranged from EUR 2.0 to 17 per kilogramme of NH_3 reduced depending on the farm type. The average benefits per kilogramme of NH_3 reduced were EUR 14.1 for health and EUR 10.4 for biodiversity. The analysis with the farm model is considered more appropriate than recent analyses at technical or macroeconomic level, because the abatement costs reflect difference in farm types, detailed production processes and farmers' profit-maximising behaviour. Moreover, farm type specific abatement strategies can be developed. Including the monetised impacts on biodiversity for the first time increased the total benefit estimate by 75% and improved the soundness of the benefit estimates. Therefore the assessment should include impacts of NH_3 emissions both on human health and on biodiversity. This modelling approach enables to estimate abatement costs for farmers and benefits for human health and biodiversity and to identify cost-efficient NH_3 abatement measures tailored to farm types. It can be applied to other air pollutant abatement measures in agriculture and to all Member States of the European Union.

Keywords: agricultural modelling; air pollution control; bioeconomic modelling; environmental impact assessment; health damage; biodiversity loss

2.1 Introduction

Ammonia (NH_3) is an air pollutant and may have adverse impacts on the environment and on human health. After emission to the atmosphere, NH_3 is subject to dispersion and transport and is either quickly deposited close to its source or converted into ammonium aerosols travelling over long distances before being deposited. Aerosols are part of the fine particle fraction (diameter <2.5µm). Hence, NH_3 is a precursor for secondary fine particulate matter ($PM_{2.5}$). After deposition to land, NH_3 can contribute to the acidification and eutrophication of natural ecosystems and to the loss of terrestrial biodiversity. It can form the greenhouse gas nitrous oxide, affecting the climate, or nitrates that can leach into ground and surface waters, affecting aquatic biodiversity (Krupa, 2003). The atmospheric deposition of NH_3 is considered a major threat to terrestrial biodiversity in Europe (Dise et al., 2011; Townsend, 2010). $PM_{2.5}$ emissions may cause respiratory and cardiovascular diseases and a reduction in life expectancy (Brunekreef and Holgate, 2002; World Health Organization, 2013).

To reduce the health and environmental damages that NH_3 emissions cause, air quality policies in the European Union (EU) and beyond demand their reduction (European Communities, 2001a, 2001b, 2008, 2010, 2005; United Nations Economic Commission for Europe, 1999). Also the EU goal to halt the loss of biodiversity relates to NH_3, e.g. by referring to the indirect fertilisation of nature preserve areas through deposition (European Communities, 2006).

About 95% of all NH_3 emissions in Germany in 2012 (545 gigagram [Gg]) originated from agriculture, with 80% from livestock manure and 20% from mineral fertiliser application (Umweltbundesamt, 2013). Recent news, however, indicate that annual NH_3 emissions in Germany were about 670 Gg in past years and thus exceeded the NH_3 emission ceiling at 550 Gg that had been agreed in air quality legislation (Fisser, 11.4.15; Kuhr, 11.4.15). Hence, the implementation of effective NH_3 emission abatement measures in the agricultural sector is crucial for NH_3 emission reduction and for compliance with air quality policy.

A common criterion for the selection of suitable NH_3 emission abatement measures is their abatement costs for farmers. Abatement costs can be estimated in various approaches (Vermont and De Cara, 2010). Some studies have estimated the potentials and costs of NH_3 emission abatement in engineering approaches. They described technical reduction potentials and costs (Döhler et al., 2011) or analysed implementations of measures to meet specific reduction targets at least cost to farming and obtained cost curves (Webb et al., 2006) (NARSES model) (Amann et al., 1999; Holland et al., 2005b) (RAINS model). Few studies included an economic model into their engineering approach (Oenema et al., 2009) (MITERRA model, CAPRI model).

From an economic welfare point of view, abatement measures need to be evaluated not only with regards to their costs for farmers, but also as to their benefits for society. Measures may only be implemented if benefits exceed abatement costs. Benefits result from damage costs that are avoided by the abatement of NH_3 emissions, which again are derived by monetising impacts of NH_3 emissions. Benefits can be estimated in impact assessments following NH_3 emissions along their pathway from the location of origin through the atmosphere to the location of impact. Thus, to link emissions to impacts, the location of origin and the atmospheric processes need to be known or simulated. The dispersion and conversion of NH_3 in the atmosphere and its deposition are simulated with atmospheric dispersion models. They work at spatially explicit grid levels at various spatial scales and need geo-referenced NH_3 emission data as input (e.g., Norwegian Meteorological Institute, 2012; Stern, 2009). However, emissions estimated in agricultural modelling approaches usually refer to administrative and not to geo-referenced units. Approaches linking these units have been developed in Leip et al. (2008) and Weinmann et al. (2006).

Some studies estimated the health damage costs caused by NH_3 emissions, and few assessed the impacts on biodiversity with a critical load exceedance approach (Brandt et al., 2013; Holland, 2012, 2014; Holland and King, 1999; Holland et al., 2005b, 2005c; Pye et al., 2008). However, it has been recognised that impacts on biodiversity should also be expressed in monetary terms, resulting in more reliable benefit estimates (European Communities, 2005).

The aim of this study is estimating and comparing costs and benefits of NH_3 emission abatement measures and thereby identifying cost-efficient measures in agriculture with a bottom-up approach at a spatially explicit scale. To this end, we combined two models: a bioeconomic farm model estimating NH_3 emission abatement potentials and costs of abatement measures at the farm and at the regional level, and an integrated environmental assessment model estimating benefits in terms of avoided damage costs of health damages and biodiversity loss. We reasoned that including farmers' economic behavioural responses at the farm level in addition to mere technical costs in the farm model would result in more appropriate estimates of farmers' abatement costs. Quantifying benefits of reduction measures and including different types of damages, such as those on human health and biodiversity, would avoid underestimating total benefits and provide more reliable benefit estimates.

Our modelling approach assessed a selection of promising NH_3 emission abatement measures. The analysis focused on a case study of the north-western German Federal State of Lower Saxony, because most of the NH_3 emissions in Germany originate in this region marked by intensive livestock husbandry and high livestock density. This approach is also applicable to other air pollutants in agriculture and to the evaluation of abatement measures simultaneously affecting different types of atmospheric emissions and different types of damages, as shown in Wagner et al. (2015) and to all EU Member States.

2.2 Method

2.2.1 Overview

We combined the bioeconomic farm model EFEM (Economic Farm Emission Model, Neufeldt and Schäfer, 2008; Neufeldt et al., 2006) and the environmental impact assessment model EcoSense. In the past, the latter model had been applied to the energy sector (Bickel and Friedrich, 2005; Krewitt, 1999; Preiss and Klotz, 2008). EFEM estimated NH_3 emissions, abatement potentials and abatement costs, while EcoSense estimated the benefits of NH_3 emission abatement. The analysis followed the impact-pathway-approach that traces the air pollutant from its source along its dispersion and conversion in the atmosphere to the affected receptors (e.g. human population, ecosystems and materials), complemented by the monetary valuation of physical impacts. This approach comprises four steps, categorized into emissions, dispersion, impact and costs (Figure 2-1).

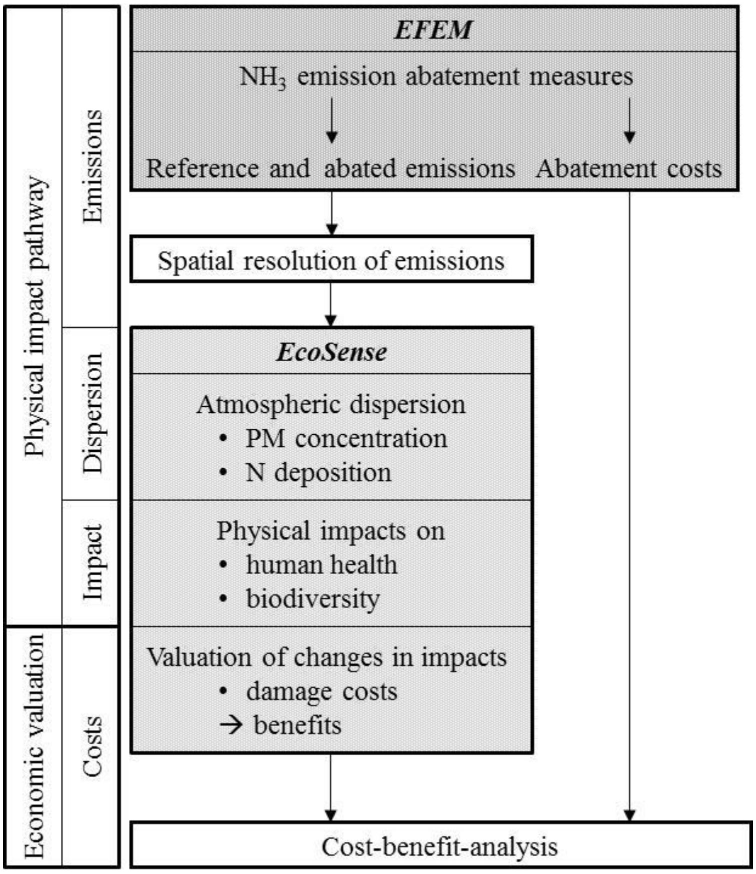

Figure 2-1: Evaluation of NH_3 emission abatement measures: estimating emissions and abatement costs with the bioeconomic farm model EFEM and benefits with the environmental impact assessment model EcoSense

Emissions: Abatement measures, their abatement potentials and related abatement costs were analysed. Emission results of EFEM at the administrative level were geo-referenced and linked to the grid level of EcoSense in a spatial resolution procedure.

Dispersion: Subsequent atmospheric dispersion modelling simulated the passage of NH_3 and its chemical reactions in the atmosphere and resulted in particulate matter (PM) concentration and nitrogen (N) deposition.

Impact: The physical impacts of changes in PM concentration on human health and of changes in N deposition on terrestrial biodiversity were estimated.

Costs: The physical impacts were weighed with monetary values and aggregated into one value, the damage costs. The damage costs that are avoided by NH_3 emission abatement represent the benefits of NH_3 emission abatement and are finally compared to the farmers' abatement costs.

2.2.2 Emissions and Abatement Costs

The model EFEM is a static linear supply model maximising farms' gross margins. Production factors, prices and production capacities in the model are exogenous. The production module depicts crop and livestock production activities differing across regions regarding yields, intensities, performance and costs. It also estimates NH_3 emissions from manure and fertiliser management in crop and livestock production activities and includes NH_3 emission abatement measures. The NH_3 emission factors are livestock-specific (e.g. dairy cows, bulls, sows, fattening pigs, laying hens and broilers) and distinguish between housing systems (e.g. slurry-based or straw-based cattle housing systems) (Haenel, 2010). In a mass-flow approach, the model distinguishes the emission sources of livestock housing, manure storage, manure application and fertiliser application. It traces NH_3 emissions along these stages including interactions, because reductions at earlier stages have impacts on the N content of manure and on NH_3 emissions and abatement potentials in subsequent stages. It considers also indirect costs, such as the reduction in mineral fertiliser use caused by the higher N content in manure.

EFEM is based on virtual typical farms that represent average farms of existing farm types. The typical farms were derived from analyses of datasets of the Farm Accountancy Data Network (FADN) and follow the FADN classification system in which the specialisation is based on the contributions of the different lines of production to the total standard gross margin (specialist field crops, specialist grazing livestock, specialist pigs, specialist poultry, mixed crops-livestock) (European Communities, 2009). The farms' production capacities and factor endowments define the linear optimisation process and its outcome. The results at the farm level are extrapolated to the regional level with a Linear Extrapolation Approach that minimises the sum of absolute deviations of modelled regional production capacities compared to official statistical data (Kazenwadel, 1999). Thus, the regional analysis is based on a bottom-up approach. Maintaining region-specific typical farms as modelling units assures that real farms are represented with respect to factor endowment, while extrapolation controls the regional production capacities and the farm structure. The EFEM results depict the structure of production and associated emissions as well as the costs and revenues at the farm and at NUTS-1-levels (Nomenclature of Units Territorial Statistics European Communities, 2003, Federal State level). EFEM can also be applied to other EU Member States. EFEM is calibrated to regional statistics from the Farm Structure Survey 2003 (Research Data Centre of the Federal Statistical Office Germany[1]) and validated by comparing modelling results for the regional capacities of livestock numbers and agricultural production to the statistical data.

This case study is carried out for Lower Saxony, a region in northwest Germany. It covers 2.6 million hectares (ha) of agricultural area, thereof about 70% of arable land and 30% of grassland. 77% of its 39,500 farms keep livestock. Livestock comprises 2.6 million heads of cattle, 8.7 million pigs, 18.6 million laying hens and 64.4 million broilers. The livestock density of 1.2 livestock units per ha exceeds the German average of 0.8 livestock units per ha and is the highest of all regions in Germany (DESTATIS, 2007; NMELV, 2013).

2.2.3 Dispersion, Impacts and Damage Costs

EcoSense has a modular structure and consists of air quality and impact assessment modules. The atmospheric dispersion module links emissions to pollution concentrations or depositions. To estimate subsequent physical impacts on human health and on terrestrial biodiversity, EcoSense holds concentration-response-functions as well as population and land use data. To valuate these physical impacts and estimate damage costs, EcoSense holds databases with monetary values for health and biodiversity impacts. EcoSense covers Europe and the Northern Hemisphere.

2.2.3.1 Spatial Resolution of Emissions

Emission results of EFEM were allocated from administrative levels in Lower Saxony to grid cells by intersection of administrative boundary data, grid data and land use data (Figure 2-2) (European Environment Agency, 2007). We calculated the share of agricultural land within each grid cell and allocated NH_3 emissions to each grid cell weighed by this share (Wagner et al., 2009). Emission sources are classified into point sources, line sources and area sources (European Environment Agency, 2013). Emissions from animal houses and manure storages are point sources, but they were treated as diffuse sources because, for reasons of data security, their coordinates were not

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[1] Data were retrieved from www.forschungsdatenzentrum.de.

available. Emissions from manure application are diffuse area sources. They were treated as uniform per ha of agricultural land, but usually they differ according to crop fertilisation requirements.

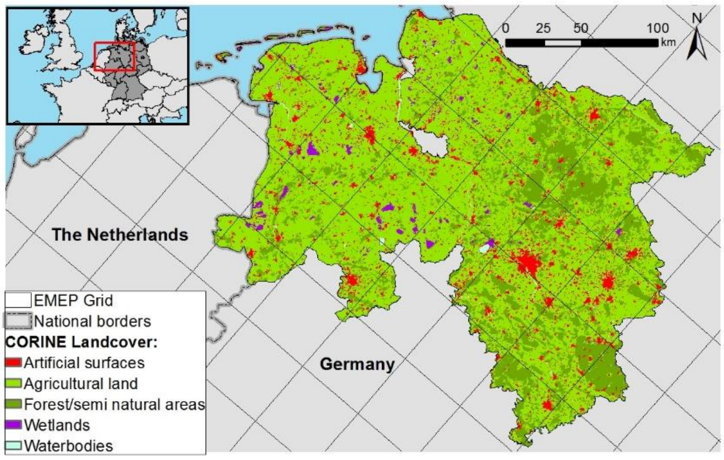

Figure 2-2: Intersection of administrative boundary data for Lower Saxony, EMEP grid data and CORINE land use data

More detailed approaches are, for example, statistical downscaling, where a statistical estimator assigns the shares of crop types to so-called Homogenous Soil Mapping Units (Leip et al., 2008), or the model ProLand, where crops are assigned to georeferenced land units by maximising land rent (Weinmann et al., 2006). Statistical downscaling is also a static approach, and the model ProLand has not been calibrated to Lower Saxony and cannot be transferred to this region without further research (Sheridan, 2010). The spatial resolution procedure in this study may be coarse, but is considered satisfying for the spatial requirements of the subsequent dispersion modelling.

2.2.3.2 Atmospheric Dispersion

The atmospheric dispersion module consists of meteorological data, referred to as source-receptor matrices. These matrices derived from the European Monitoring and Evaluation Programme (EMEP) dispersion model (Norwegian Meteorological Institute, 2012). They detailed the long-range transport of NH_3 emissions of source grid cells and their chemical reactions in the atmosphere to $PM_{2.5}$ concentration levels for human population or N deposition levels for terrestrial ecosystems in affected grid cells. This way, impacts from secondary particles were assigned to NH_3 emissions and not to PM concentrations. The matrices represented an average of the years 2000 to 2010 to avoid a bias due to meteorological patterns in any given year. The chemical transformation of NH_3 into $PM_{2.5}$ depends both on meteorological data and on background concentrations of air pollutants of all sectors. They affect the chemical transformation of NH_3, because its reactions with background pollutants are non-linear, and they can also form PM. The contribution of NH_3 emissions to overall air pollution levels, the so-called deltaconcentration, is identified in two model runs: one run including all emission types and one run including all emissions minus the specific emission of interest, here NH_3.

2.2.3.3 Impacts on human Health and on terrestrial Biodiversity

The impacts on human health were estimated with linear concentration-response-functions that link the concentration of $PM_{2.5}$ to health impacts of morbidity or mortality and express how a change in concentration affects the number of health incidences (Torfs et al., 2007). Morbidity impacts comprised additional cases of chronic bronchitis in adults, restricted activity days, hospital admission and medication use and were expressed in Disability Adjusted Life Years. Impacts on premature mortality were expressed in a reduction in life expectancy with the metric of Years Of Life Lost. Health impacts were estimated by combining concentration-response-functions and population numbers in a grid cell (SEDAC, 2006). As health effects occur on long-term exposure, they refer to cases of illness in the longer run caused by NH_3 emitted in a certain year, here 2015.

The impacts on terrestrial biodiversity caused by acidification and eutrophication due to N deposition were estimated based on the Potentially Disappeared Fractions (PDF) concept developed for the Netherlands (Goedkoop and Spriensma, 1999; Latour et al., 1997). The PDF indicator measures changes in plant species biodiversity, i.e. the number of species living in a certain area, over area and time. The relative decrease of the number of species per area and time expresses the loss of biodiversity. However, eutrophication can lead to an increase in species number. Therefore the PDF refers to target species, i.e. species that are considered typical and representative for a specific type of natural ecosystem without anthropogenic effects. The approach covers 900 plant species in more than 40 types of ecosystems. The PDF gives the percentage of target species which are likely to disappear due to unfavourable conditions compared to natural ecosystems. It was assumed that the PDF factor for the Netherlands would be the same in Germany. The impacts on biodiversity were estimated by applying the PDF to the fraction of the area of natural land with critical load exceedance[2] in a grid cell (CCE).

2.2.3.4 Damage Costs

The valuation of health impacts included associated market costs, such as for medical treatment and hospital admission; opportunity costs, such as income loss; and non-market values that represent the willingness-to-pay of representative population groups to avoid the risk of illnesses and suffering or the loss of life expectancy due to air pollution (Desaigues et al., 2011; Desaigues et al., 2007). For example, the value of avoiding an asthma attack includes both the cost of the medical treatment and the willingness-to-pay to avoid the residual suffering. The damage costs

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[2] Data retrieved from the Coordination Centre for Effects (CCE), http://wge-cce.org.

represent net present values of future incidences discounted to the year 2015. A discount rate of 3% was assumed until 2030 and of 2% between 2030 and 2050.

The monetary values of ecosystem damages included in EcoSense were based on a meta-analysis of willingness-to-pay studies to protect biodiversity (Kuik et al., 2007). The damage costs for Germany were estimated at EUR 0.51 (Euro_{2004}) per PDF and square metre.

2.2.4 Abatement Measures and Scenarios

NH_3 emissions from manure storages can be reduced with flexible storage cover techniques, such as floating plastic covers, or with rigid cover techniques, such as a concrete cover. Emissions from manure application can be reduced with, e.g., trailing shoe or cultivator and injection techniques. These measures are listed among the good agricultural practices given in the Gothenburg Protocol or the EU Directive on National Emission Ceilings (European Communities, 2001a; United Nations Economic Commission for Europe, 1999). Detailed descriptions of these measures can be found, e.g., in Döhler et al. (2011). Table 2-1 gives the potential of NH_3 emission reductions and the annual technical costs per measure as included in EFEM (based on Achilles, 2002; Achilles and Frisch, 2000; Döhler, 2005; Haenel, 2010). The costs for manure storage techniques refer to storage capacities of a volume of 500 cubic metres. The costs for application techniques were derived from contractors' costs in the German Federal State of Bavaria and adapted to farm sizes in Lower Saxony. All costs were adjusted to the year 2015.

Table 2-1: NH_3 emission reductions (in %) and average annual costs (in EUR) for manure storage cover and manure application techniques for Lower Saxony, Germany, used as input data for EFEM

	NH_3 reduction	**Annual costs**	**Applicability**
Manure storage cover			
No cover			
Floating plastic cover	85 (80-90)	EUR 1,304	Low maintenance requirements
Concrete cover	90 (85-95)	EUR 1,527	Low maintenance requirements, no precipitation input
Manure application			
Broadcast		Liquid: 3.4 EUR/m³ Solid: 4.3 EUR/m³	
Trailing shoe arable land	60	5.9 EUR/m³	For growing crops and grassland
Trailing shoe grassland	50 (40-60)		
Cultivator	80	6.7 EUR/m³	Not for growing crops or grassland
Injector	70 (60-80)	6.3 EUR/m³	For growing crops and grassland

m³ = cubic metre
Source: Achilles (2002); Achilles and Frisch (2000); Döhler (2005); Haenel (2010)

The abatement measures were analysed in two scenarios: a reference scenario that estimated emissions under the current level of abatement measures (Osterburg and Dämmgen, 2009), and an abatement scenario assuming that the abatement measures were implemented on all farms. Also, combinations of storage and application measures were analysed in scenarios and compared to the references. The scenario Float_Shoe combined floating plastic cover and trailing shoe, and the scenario Conc_Inject combined concrete cover and a cultivator for slurry application on uncultivated arable land and injection techniques for slurry application on growing crops on arable land and on grassland.

2.2.5 Uncertainty Assessment

An uncertainty assessment was carried out in three steps on the basis of Sabel et al. (2011) and Zenié and Meek (2008): First, the sources of uncertainty were identified. Second, the uncertainty was characterised by assessing its direction on the results and the level of uncertainty of the source. The direction of uncertainty indicates how the source of uncertainty is deemed to affect the results. The results are considered to be overestimated, underestimated or, if either direction is possible, as both. The level of uncertainty itself is considered to be low, medium or high. Third, the knowledge base of the uncertainty source is assessed, where low indicates confidence in the data and their applicability to the assessment, medium implies that some limitations of scientific evidence and applicability exist and high indicates that the knowledge base is very limited. Finally, a justification text in the uncertainty assessment matrix gives the arguments to justify the scoring of the uncertainty assessment and to increase transparency.

2.3 Results

2.3.1 Emissions, Abatement Costs and Benefits

At the farm-type level, pig specialists yielded the highest gross margins per ha but also caused the highest NH_3 emissions per ha in the reference situation (Table 2-2). In contrast, field crop specialists earned lower gross margins but caused only about 10% of NH_3 emissions per ha. The potential of NH_3 emission reductions was highest at farm types with high NH_3 emissions in the reference situation. Reductions in gross margins caused by NH_3 emission abatement ranged from 0.2 to 3.5%. Those measures with the highest reductions in gross margins were cultivator and injection techniques on grazing livestock specialists.

Manure storage cover techniques achieved high reductions on pig and poultry specialist farms, while manure application techniques achieved high reductions in NH_3 emissions (25%) on grazing livestock farms. This difference is explained by the characteristics of the manure types. During the storage of manure, cattle slurry with its high content of dry-matter quickly forms a natural crust that reduces NH_3 emissions, whereas pig slurry has on average a lower dry-matter content and hardly forms a crust. After slurry application, the high dry-matter content of cattle slurry hinders a quick infiltration of the slurry into the soil and thereby leads to higher NH_3 emissions as compared to pig slurry with comparably low dry-matter content. The low dry-matter content of pig slurry, however, leads to higher NH_3 emissions during manure storage.

Table 2-2: Gross margins (in EUR) and NH_3 emissions (in kg per ha) in the reference situation, and their reductions (in %) caused by abatement measures per farm type in Lower Saxony, Germany

		Farm type				
		Field crops specialists	**Grazing livestock specialists**	**Pig specialists**	**Poultry specialists**	**Mixed crops-livestock**
		Reference				
Reference	Gross margin (EUR per ha)	1,000	1,710	3,686	2,273	1,289
	NH_3 emissions (kg per ha)	8.1	52.6	86.1	64.0	28.3
		Reductions compared to the reference (%)				
Manure storage cover						
Floating plastic cover	Gross margin	n/a	0.8	1.2	0.8	0.8
	NH_3 emissions	n/a	10.7	13.7	9.1	2.2
Concrete cover	Gross margin	n/a	1.0	1.1	0.6	0.6
	NH_3 emissions	n/a	6.5	15.1	9.9	2.4
Manure application						
Trailing shoe	Gross margin	n/a	3.0	1.7	1.2	0.8
	NH_3 emissions	n/a	21.8	6.7	4.7	5.9
Cultivator/Injector	Gross margin	n/a	3.5	1.8	1.3	0.9
	NH_3 emissions	n/a	24.7	7.2	4.8	6.5

n/a = not applicable
Own calculations with EFEM

The abatement costs vary per farm type according to the reductions in gross margins and in NH_3 emissions (Table 2-3). The abatement costs of floating plastic covers were higher than those of concrete covers on average and for all farm types except for grazing livestock specialists. The abatement costs of manure covers were highest on mixed crops-livestock farms. The abatement costs of trailing shoe or cultivator and injector differed only slightly. They were lowest on grazing livestock farms.

Table 2-3: NH_3 emission abatement costs (in EUR per kg NH_3) per farm type in Lower Saxony, Germany

	Farm type				
	Grazing livestock specialists	**Pig specialists**	**Poultry specialists**	**Mixed crops-livestock**	**All farms**
Manure storage cover					
Floating plastic cover	2.43	3.75	3.12	16.57	4.2
Concrete cover	5.00	3.12	2.15	11.39	3.6
Manure application					
Trailing shoe	4.48	10.86	9.07	6.18	6.8
Cultivator/Injector	4.61	10.70	9.62	6.31	6.7

Own calculations with EFEM

Table 2-4 shows the amount of NH_3 emissions abated via manure storage cover and application with the combination of abatement measures and the related abatement costs, compared to the reference scenario. The abatement costs resulted from decreases in gross margins caused by the implementation of the abatement measure. The combination of concrete cover and cultivator/injector was the most cost-effective measure, with EUR 5.9 per kilogramme (kg) NH_3 reduced. This measure had the highest costs per cubic metre of manure stored and applied but also the highest reduction potential, resulting in lower average abatement costs than for the scenario Float_Shoe.

Table 2-4: NH_3 emissions, gross margins and average abatement costs for the combinations of manure storage cover and manure application techniques, Lower Saxony, Germany

			Scenarios	
	Unit	**Reference**	**Float_Shoe**	**Conc_Inject**
NH_3 emissions	Gg	108.3	85.6	81.2
NH_3 reduction	%	--	21	25
Gross margin	Million EUR	4,401	4,244	4,242
Abatement costs	EUR per kg NH_3	--	6.9	5.9

Own calculations with EFEM

The reduction of NH_3 emissions realisable in the scenario Conc_Inject prevented 3,700 Years Of Life Lost, i.e. it extended the life expectancy by 3,700 years, and prevented 2,338 Disability Adjusted Life Years as compared to the reference scenario (Table 2-5). The average benefits were estimated at EUR 24.5 per kg NH_3 reduced, with benefits of EUR 14.1 per kg NH_3 reduced for avoided health damages and EUR 10.4 per kg NH_3 reduced for avoided biodiversity loss. These results show that the health damage costs that were caused by secondary particles formed from

NH_3 emissions were higher than biodiversity damage costs. On the other hand, the total damage costs including biodiversity impacts increased by 75% as compared to an assessment that includes only health damages and does not valuate biodiversity impacts.

The comparison of farmers' abatement costs to society's benefits showed that the abatement costs of all abatement measures were lower than the society's benefits. Implementing the scenario Conc_Inject avoided EUR 664 million of damage costs and, including farmer's abatement costs, yielded the highest net benefits (i.e., total benefits minus abatement costs), amounting to EUR 505 million, and the highest benefit-to-cost ratio at 4.2. In this case, EUR 1 invested in NH_3 emission abatement would yield EUR 4.2 for the society.

Table 2-5: Impacts and benefits of NH_3 emission abatement and comparison to abatement costs, Lower Saxony, Germany

			Scenarios	
	Unit	**Reference**	**Float_Shoe**	**Conc_Inject**
Health impacts:				
reduced life expectancy	YOLL	14,540	11,475	10,840
morbidity	DALY	9,188	7,251	6,850
Damage costs health	Million EUR	1,522	1,202	1,142
Damage costs biodiversity	Million EUR	1,135	897	851
Total Benefits	Million EUR		558	664
Net benefits	Million EUR		401	505
Benefit-to-cost ratio	-		3.6	4.2

YOLL =Years of Life Lost; DALY = Disability Adjusted Life Year
Own calculations with EcoSense

Sensitivity analyses[3] showed that when varying abatement potentials, abatement costs and avoided damage costs, the abatement measures were consistently cost-efficient. A variation in abatement potentials had only little influence on the cost-efficiency of the abatement measures.

2.3.2 Uncertainty Assessment

The assessment of the potential sources of uncertainty is presented in Table 2-6. The qualitative assessment of uncertainty of the benefit estimates identified the concentration-response functions for health impacts, the potentially disappeared fractions for biodiversity impacts and non-market health and biodiversity damage costs as the main sources of uncertainty along the impact-pathway chain. These sources of uncertainty are further discussed in the text below.

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[3] The abatement potentials varied according to the ranges given in Table 1. The abatement costs varied by +300%. The benefits for NH_3 emissions varied between -67% and +200% (Spadaro and Rabl, 2008).

Table 2-6: Uncertainty assessment matrix

Sources of uncertainty	Direction of uncertainty	Level of uncertainty	Appraisal of uncertainty of knowledge base	Justification of the overall uncertainty assessment
Emission modelling				
Livestock data	under	low	low	Based on official statistical data
NH_3 emission factors	both	medium	low	Based on German Emission Inventory Report (Haenel, 2010)
Abatement potentials	over	low	low	Due to optimisation of farm management in the modelling simulation
Dispersion modelling				
Source-receptor matrices		low	low	Scientifically applied and accepted in air quality policy assessments[1]; validated with measurements
Health impacts				
Concentration-response function	over	medium	low	Applied in scientific analyses of EU air pollution policies, supported by the WHO; concentration does not equal intake; limited evidence of effects of secondary PM from nitrate fraction
Population data	both	low	low	Deviation of gridded data to national census data less than 5%[2];also applied by the European Commission Joint Research Centre (EDGAR)[3]
Biodiversity impacts				
Potentially disappeared fractions		high	medium	Scientifically applied and politically accepted in the Netherlands; validated with measurements[4]; transfer of fractions to Lower Saxony uncertain
Land use data		low	low	Scientifically applied and politically accepted in European air pollution policies (e.g. CLRTAP)[5]
Monetary valuation				
Market health damage costs		low	low	Based on official statistical data
Non-market health damage costs		medium	medium	Based on few willingness-to-pay studies, values lower than in other studies
Biodiversity damage costs		medium	medium	Based on meta-analysis of willingness-to-pay studies; values are similar to restoration costs

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[1] Scientifically based and policy driven under the Convention on long-range transboundary air pollution (CLRTAP); http://www.emep.int/

[2] http://sedac.ciesin.columbia.edu/data/collection/gpw-v3/methods/method1

[3] http://edgar.jrc.ec.europa.eu/kml_files_intro.php

[4] http://www.pbl.nl/publicaties/2007/Natuurplanner3.0_beschrijvingenhandleiding

[5] http://wge-cce.org/Methods_Data

Linear concentration-response-functions are applied in air quality policy assessments and other studies (Brandt et al., 2013; Holland et al., 2005b; United Nations Economic Commission for Europe, 2004). The causal association between particles and health effects, however, may be limited, because interactions with co-emitted pollutants can influence human response when compared to particles alone (Moldanová et al., 2011). Treating all particles as equally harmful to health, as recommended by the World Health Organization (World Health Organization, 2007), disregarding individual chemical components, may be associated with uncertainty. Substantial epidemiological evidence of associations between health risks and sulphate fraction exist (e.g., Pope III et al., 2002), but the evidence base for the nitrate fraction may need to be strengthened (Moldanová et al., 2011; Reiss et al., 2007). Attributing higher risks to primary particles compared to secondary particle (Andersson et al., 2009) reduced health damage costs of NH_3 emissions (Brandt et al., 2013) and would influence the assessment of NH_3 emission abatement measures.

The non-market health damage costs mainly depend on the values for reduced life expectancy and chronic bronchitis. The value for reduced life expectancy, based on the metric of Value Of a Life Year, of EUR 40,000 is lower than the values that were applied in the assessment of EU air quality policies ranging from EUR 52,000 to EUR 120,000 (Holland et al., 2005a; Holland et al., 2005b, 2005c; Pye et al., 2008; Pye et al., 2007). The value for a case of chronic bronchitis of EUR 200,000 is between the values applied by Pérez et al. (2009) of EUR 125,000 to EUR 260,000 ($Euro_{2006}$). Our estimates for reduced life expectancy and cases of chronic bronchitis are similar to those found in other studies and are considered appropriate.

The impacts on biodiversity were estimated with a PDF factor for natural landscape conditions in the Netherlands. It was derived from the Dutch ecologic model “natuurplanner”, which is considered a sophisticated model and widely applied in governmental or university research institutions in the Netherlands. It covers ecosystems and plant species that are typical for the Netherlands, but does not reflect conditions in Germany. While the natural ecosystems in both the Netherlands and Germany are threatened by high pressures of acidification and eutrophication (Ott et al., 2006), transferring the Dutch PDF to Lower Saxony neglects the differences in geography, ecosystem composition and background deposition and is associated with a high degree of uncertainty. Studies for Germany, and in this case specifically for Lower Saxony, were not available.

The monetary value assigned to a change in PDF is based on a meta-analysis of global willingness-to-pay studies to protect biodiversity. The value used in this study is very similar to the minimum restoration costs of increasing biodiversity by changing from a land use type with low plant species richness to a land use type with high species richness in Germany (Ott et al., 2006). The small difference in these values enhances the confidence in the applied value.

2.4 Discussion

In this study, a cost-benefit analysis constitutes the framework for assessing NH_3 emission abatement measures. As we focused on a single pollutant, the abatement measures could have been assessed in a cost-effectiveness analysis without the effort of monetising impacts. Yet we see advantages of estimating and monetising impacts for mainly two reasons. First, damage costs represent the external costs of agricultural production, and estimating them is a precondition for internalising external costs. The comparison of abatement costs and damage costs determines the quantity of NH_3 emissions to be reduced to increase welfare gains and the optimum emission level or reduction level, and indicates whether reduction targets are too ambitious or too weak. In our case, the exceedance of the society's benefits over farmers' abatement costs suggests that the emission reduction can be more ambitious than currently achieved. It may also indicate possible scope for subsidising farmers to abate NH_3 emissions. Second, the monetisation of impacts is advantageous if abatement measures affect various pollutants or various effects, because they need a common unit to be comparable. Climate change mitigation measures affecting different types of greenhouse gases can be commonly assessed, because they can be linked by their global warming potential to the common unit carbon dioxide equivalents and because they have the same effect of climate change. NH_3 emission abatement measures may affect other nitrogen emissions (Oenema et al., 2009). Relating them to nitrogen as common unit would neglect the differences in impacts on the environment and on human health. In the case of interrelations with methane emissions (Brink et al., 2005), no such common unit exists. When several emission types are included, the most cost-effective measure cannot be identified and a cost-effectiveness approach has its limitations (Brink et al., 2005). Eory et al. (2013) include monetary values of the external effects of measures on pollution loads other than the target emissions in their assessment and, in doing so, draw close to a cost-benefit approach. Combining various pollutants and effects, Wagner et al. (2015) analyse interactions among air pollutant abatement and greenhouse gas emissions in a cost-benefit-analysis. Concluding this reasoning, monetising impacts and estimating damage costs is an appropriate and useful approach in multi-dimensional assessments.

The abatement cost estimates of EFEM range in the middle to upper bound compared to other studies (Döhler et al., 2011; Oenema et al., 2009; Wagner et al., 2012; Webb et al., 2006) (Table 2-7). These values need be compared with caution, because they were derived in different modelling approaches. Vermont and De Cara (2010) distinguish engineering approaches, supply-side models and equilibrium models. Most of the studies assessing NH_3 emission abatement costs can be considered engineering approaches (Amann et al., 2005; Amann et al., 1999; Döhler et al., 2011; Wagner et al., 2012; Webb et al., 2006). They estimate technical costs and the cost-effectiveness of abatement measures and partly derive cost curves. Oenema et al. (2009) complement the engineering approach with an equilibrium model and estimate abatement costs at the agricultural sector level and impacts on consumer incomes. These approaches, however, do not analyse impacts on the farm activities nor do they consider farm types. Representing a supply-side model, EFEM analyses production processes, related emissions, abatement measures and production costs, including gross margins at farm level. This approach reflects different farm types, detailed production processes and farmers' profit-maximising behavioural responses to the implementation of abatement measures. It can underlie the development of farm-type specific NH_3 emission abatement strategies. EFEM does not depict interactions among farms because of its linear extrapolation from farm to regional level. Such interactions could be analysed in agent-based models or multi-agent systems (Berger and Troost, 2014). However, to our knowledge, no such agent-based model exists that describes production processes and related NH_3 emissions and abatement measures in such a detailed way as EFEM does. Unlike equilibrium models, EFEM does not include the demand for agricultural products and thus no indirect effects on the supply through the change in equilibrium prices. To include such an impact while assuring a high level of disaggregation and farm type characteristics, EFEM could be coupled with an agricultural partial equilibrium model (Deppermann et al., 2014). In this respect, our supply-side modelling approach has its limitations. Nevertheless our approach constitutes an advantage compared to the engineering approaches that have been applied in air quality policy analyses.

Table 2-7: Average NH_3 emission abatement cost estimates in other studies (in EUR per kg NH_3)

	Döhler et al. 2011	**Webb et al. 2006**[*]		**GAINS model**[**]
Spatial reference	Germany	United Kingdom		Germany
Unit	EUR per kg NH_3	EUR per kg NH_3		EUR per kg NH_3
Measure			Category	
Manure storage cover				
Natural crust		0.5-2.2^{b}		
Light bulk material	0.3-0.4^{a}		Low efficiency	0.5^{a}
	1.3-1.8^{b}			2.9-3.0^{b}
Floating/flexible cover	0.4-1.3^{a}	8.9^{b}		
	2.1-6.3^{b}	0.9^{a}		
Rigid/concrete cover	1.3^{a}	10.0^{a}	High efficiency	0.8^{a}
	6.2^{b}			7.4^{b}
Manure application				
Trailing hose	0.3-8.8^{a}		Low efficiency	1.4^{a}
	0.3-7.1^{b}			0.9-1.2^{b}
				1.0^{c}
Trailing shoe	1.9-6.3^{a}	2.8^{a}		
	1.5-5.1^{b}	6.1-6.6^{b}		
Slot Injection (Disc)	0.6-4.6^{a}	0.5-0.9^{a}	High efficiency	0.6^{a}
	0.4-3.7^{b}	0.7-1.9^{b}		0.3^{b}
		0.7^{c}		0.01^{c}
Cultivator	0.5-3.4^{a}			
	0.4-2.8^{b}			

[*] Original costs in British Pound; exchange rate as of 2006: 1 British Pound = 1.47 EUR

[**] GAINS model data base http://gains.iiasa.ac.at/models/, accessed 21 Dec 2014, own calculations

[a] pig slurry

[b] cattle slurry

[c] poultry manure

Besides the abatement costs, the cost-efficiency of an abatement measure is influenced by the benefits. These were estimated by linking physical impacts to a monetary valuation of those impacts. In spite of the uncertainties associated with the benefits, the monetary valuation of physical impacts enables the aggregation of multi-dimensional impacts and benefits in a one-dimensional welfare measure. Our results for health damage costs are mainly at the lower bound compared to estimates in other studies (Table 2-8). The ecosystem damage costs in other studies are about EUR 3 per kg NH_3 for terrestrial ecosystems and range from EUR 0.3 to 25 per kg of reactive nitrogen, depending on the ecosystem, the location and the valuation approach (Brink and Grinsven, 2011). Biodiversity damage costs in our study are at the middle to upper bound compared to other studies. The shares of health and biodiversity benefits in total benefits elucidate on the one hand the importance of NH_3 emission abatement for the reduction of secondary particles and subsequent health impacts. Pinder et al. (2007) consider NH_3 emission abatement a cost-effective means for reducing particles. On the other hand, excluding biodiversity benefits, as has been done in other studies (e.g., Brandt et al., 2013; Holland et al., 2005b, 2005c), would underestimate the total benefits. Consequently, including them in the cost-benefit-analysis increases the net benefits and the benefit-to-cost- ratios, improves the evaluation of NH_3 emission abatement measures and leads to sounder benefit estimates.

Table 2-8: Health damage costs and ecosystem damage costs in other studies (in EUR per kg NH_3)

Source	Country	Price year	**Health damage costs**	**Ecosystem damage costs**
			EUR per kg NH_3	
Brandt et al. (2011)	Denmark	n/a	34	
Bruyn et al. (2008)	Netherlands	(Euro$_{2008}$)	23	5
Holland et al. (2005a)	Germany	n/a	35	
Brink and Grinsven (2011)	Germany	n/a	27	
Brink and Grinsven (2011)	EU	(Euro$_{2000}$)	10	3

The spatial resolution and dispersion of emissions are important parts in impact assessment, because the location of origin of the NH_3 emissions and their dispersion determine the location of impacts, which in turn influence potential benefits of NH_3 emission abatement. Health impacts depend on the population number affected by changes in $PM_{2.5}$ concentration. Similarly, the impact of biodiversity depends on the coverage of natural ecosystems in which N deposits. If the $PM_{2.5}$ concentration changes in an uninhabited area or N deposition changes only on non-natural ecosystems, no benefits of the abatement of NH_3 emissions occur. Thus the benefits depend on the origin of the emissions and must be estimated separately for different regions. This approach also allows targeting NH_3 emission abatement policies at those regions causing the highest damages and developing region-specific NH_3 emission abatement policies. For this reason, however, the benefit estimates cannot be transferred to other countries without uncertainties.

2.5 Conclusions

NH_3 emission abatement reduces damages to the environment and provides benefits for the society, but imposes costs on farmers. Unlike in other studies that apply engineering approaches, the abatement costs in this supply-side modelling approach do not only reflect mere technical costs, but also capture farmers’ economic behavioural responses to the implementation of abatement measures. Moreover, the supply-side farm model analyses production processes at the farm level in more detail than can be done in other approaches. The resulting abatement cost estimates can be regarded more appropriate and, considering their variations per farm type, can contribute to farm type specific cost-efficient abatement strategies.

The abatement costs alone do not give evidence as to whether or to what extend the implementation of NH_3 emission abatement measures is justified. Such an assessment requires estimating the benefits of NH_3 emission abatement. The comparison of marginal costs and benefits indicates the optimal emission and abatement level. Positive net benefits or benefit-to-cost ratios larger than one suggest that farmers should implement those NH_3 emission abatement measures, and that public financial support, e.g. through investment aids, can be justified to enhance the implementation.

The benefit estimates in this study comprise impacts on health and biodiversity. The health benefits elucidate the importance of NH_3 emission abatement for reducing PM emissions. Including the monetised impacts on biodiversity increases the total benefit estimate and avoids underestimating the benefits of NH_3 emission abatement. The monetary evaluation of different types of externalities enables their comparison, and thereby improves the soundness of the benefit estimates and benefit-to-cost ratios.

Combining the bioeconomic farm model EFEM and the integrated environmental impact assessment model EcoSense identifies cost-efficient NH_3 emission abatement measures in agriculture. This modelling approach can be applied to other air pollutants in agriculture, especially for analysing their interactions, and to other regions, thereby contributing to farm type specific and region-specific cost-efficient air quality policy design.

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3 Costs and benefits of ammonia and particulate matter abatement in German agriculture including interactions with greenhouse gas emissions

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Abstract

Ammonia (NH_3) and particulate matter (PM) emission abatement in agriculture reduces damages to human health and biodiversity providing benefits for the society, while it imposes costs on farmers. As NH_3 and PM emissions partly originate from the same activities as greenhouse gas emissions, interactions may exists between NH_3 and PM emission abatement with greenhouse gas emissions. The objective of this study is to estimate farmers' costs and society's benefits of NH_3 and PM emission abatement measures considering interactions with greenhouse gas emissions in agriculture in Germany. An economic-ecological farm model estimating emission reductions and abatement costs and an integrated environmental impact assessment model estimating benefits for human health and biodiversity were combined for application to three Federal States in Germany. It was reasoned that benefits exceed costs and that synergies with greenhouse gas reduction exist. The results showed that all NH_3 and PM emission abatement measures affected greenhouse gas emissions. In crop production, reduced tillage increased farmers' gross margins and reduced both PM emissions and, via soil carbon sequestration, greenhouse gas emissions. The benefits depended on the soil type and its carbon sequestration potential that differ across regions. The substitution of urea fertiliser for calcium ammonium nitrate reduced both NH_3 and greenhouse gas emissions. In livestock production, chemical washers for exhaust air purification, manure application with injection or cultivator techniques and concrete manure storage cover yielded the highest net benefits. Low-protein pig feeding also achieved high net benefits, with the benefits of greenhouse gas emission reduction exceeding those of NH_3 emission reduction, and additionally increased farmers' gross margins. Low-protein poultry feeding, trailing hose and biofilters for air purification yielded negative net benefits and were therefore not recommended for implementation. The results confirm interactions of NH_3 and PM emission abatement measures with greenhouse gas emissions and suggest that all relevant emission types be integrated in an analysis. Air pollution abatement and climate change mitigation have mainly been addressed in separate policies. Our results suggest that these policies are better integrated so as to stimulate synergies and to define the appropriate ambition level of emission reduction targets.

Keywords: cost-efficiency; economic-ecological modeling; environmental impact assessment; damage costs; health; biodiversity

4 Food choices, health and environment: effects of cutting Europe's meat and dairy intake

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Abstract

Western diets are characterised by high intakes of meat, dairy products and eggs, which lead to intakes of saturated fat and red meat that are above dietary recommendations. The associated livestock production requires large areas of land and leads to high emissions of nitrogen and greenhouse gases. Although several studies have examined the potential environmental effects of dietary changes, the effects of large-scale dietary shifts on health, the agricultural system and the environment have only been studied to a limited extent. By using biophysical models and methods, we examined the large-scale consequences in the European Union (EU) of replacing 25-50% of animal-derived foods with plant-based foods on a dietary energy basis, assuming corresponding changes in production. By testing the effects of these alternative diets, we show that halving the consumption of meat, dairy products and eggs in the EU reduces nitrogen pollution from the food system by 40%, greenhouse gas emissions by 25-40% and per capita use of cropland for food production by 23%, and that it simultaneously lowers health risks. The EU becomes a net exporter of cereals and the use of soy bean meal is reduced by 75%. The nitrogen use efficiency of the food system increases from the current 18% to 41-47%, depending on choices made regarding land use. As agriculture is the major source of nitrogen pollution, this is expected to result in a significant improvement in both air and water quality in the EU. The resulting 40% reduction in saturated fat intake leads to a reduction in cardiovascular mortality. These diet-led changes in food production patterns would have a large economic impact on livestock farmers and associated supply-chain actors such as the animal feed industry and meat processing sector.

Highlights

- We model the effect of halving meat and dairy consumption on health and environment.
- Halving meat and dairy lowers saturated fat intake to the maximum recommended level.
- Lower livestock production lead to 40% lower nitrogen emissions.
- Lower livestock production lead to 25-40% lower greenhouse gas emissions.
- Lower meat and dairy consumption would make the EU an exporter of cereals.

4.1 Introduction

Western diets are characterised by high intakes of animal products, which lead to an intake of saturated fat and red meat above dietary recommendations (Linseisen et al., 2009; Ocké et al., 2009; Pan et al., 2012). Consumption of meat, dairy and eggs is increasing worldwide (FAO, 2006; Kearney, 2010), and this will aggravate the impact of livestock production on the environment (Bouwman et al., 2011; Godfray et al., 2010; Steinfeld et al., 2006; Thornton, 2010). Concerns about animal welfare, reactive nitrogen and greenhouse gas emissions have stimulated public debate in Europe about eating less meat and dairy products (Deckers, 2010; Deemer and Lobao, 2011; Freibauer et al., 2011, Garnett, 2011; Krystallis et al., 2012). This debate draws on a growing consensus in the scientific community that changing western diets may have positive outcomes for both human health and the environment (Friel et al., 2009; Godfray et al., 2010; Hawkesworth et al., 2010). There have been numerous life-cycle analyses (de Vries and de Boer, 2010; Nijdam et al., 2012; Weiss and Leip, 2012), input-output analysis (Tukker et al., 2011) and global assessments (Popp et al., 2010; Stehfest et al., 2013; Stehfest et al., 2009) of the environmental impact of meat and dairy consumption and dietary changes. However, these studies do not address the implications for the structure of regional agriculture, even though the expected resource use and environmental impacts of change are manifest most at these scales. Against this background, the central question that we have addressed is: what would be the consequences for the environment and human health if consumers in an affluent world region were to replace part of the meat, dairy produce and eggs they consume with plant based foods? We explore this question with a focus on the European Union’s 27 Member States (EU27), a region that illustrates high per-capita intake of animal protein compared with many other parts of the world.

4.2 Method and data

4.2.1 Overview

A large number of calculation steps were taken to arrive at the final estimates. The conceptual scheme used for the analysis of the effects of alternative diets is shown in Figure 4-1.

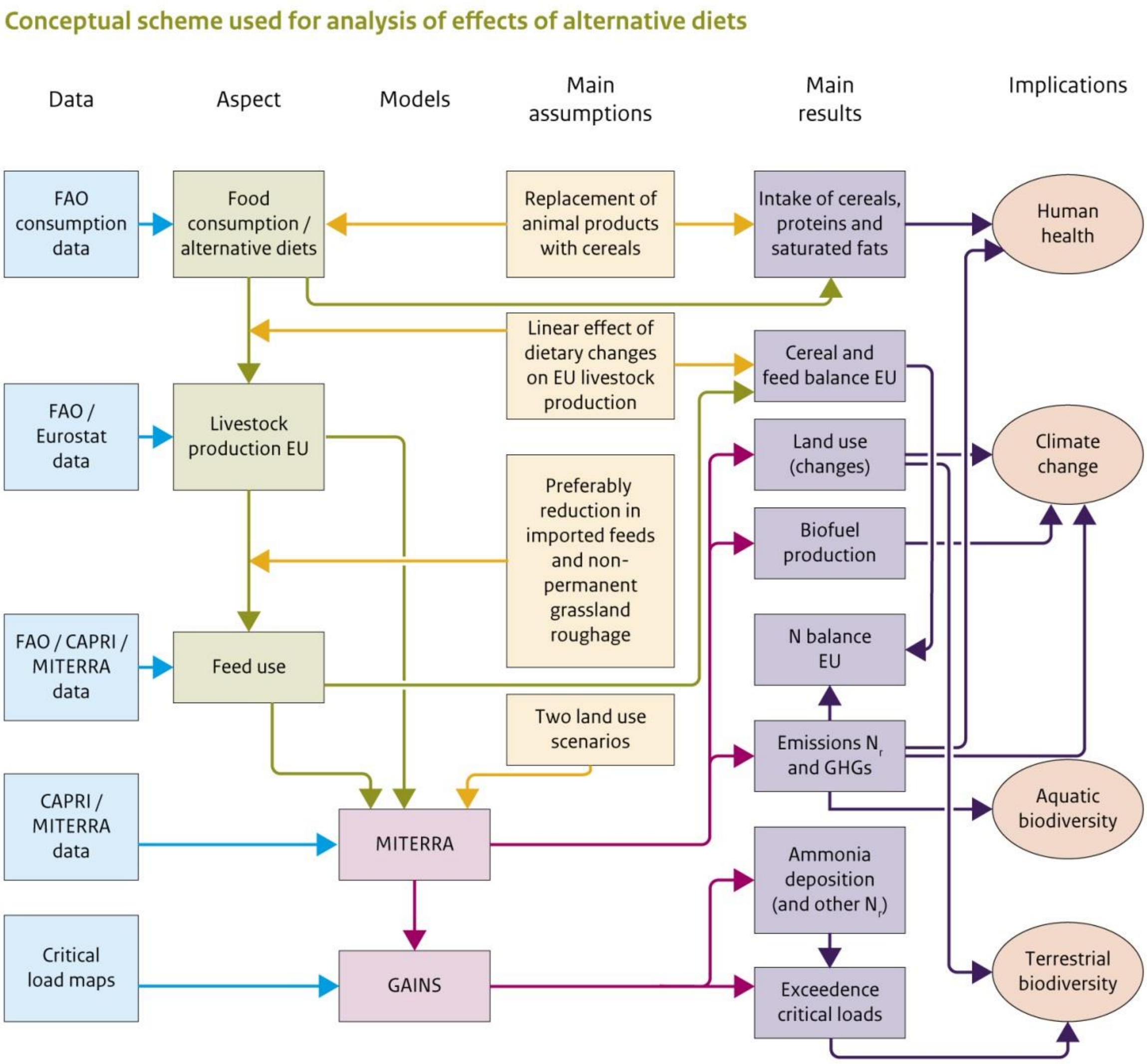


Figure 4-1: Overview of methodology, presenting data sets, models applied, main assumptions, main direct results and implications

To investigate the consequences of dietary change based on reductions in the consumption of meat, dairy and eggs, we developed six alternative diets for the EU27. In these diets, the consumption of beef, dairy, pig meat, poultry and eggs is lowered by 25% or 50%, compensated by a higher intake of cereals (Table 4-1). The assumption was made that a reduction in the consumption of meat, dairy and eggs would have a proportional effect on livestock production within the EU. Less livestock means less animal feed is needed, including forage (mostly grass and forage maize). The alternative diets therefore result in opportunities to change the use of land (arable and grassland) that is no longer needed for feeding animals. We hence explored two land-use scenarios: a greening world and a high prices world. Effects on emissions of greenhouse gases and reactive nitrogen (N), land use, the use of fertilisers and manure, and the effect on N deposition in Europe were assessed. The implementation of the alternative diets and land use scenarios has no explicit time dimension. Furthermore, only biophysical models and data were used to quantify the environmental effects. We only assessed the direct environmental effects on agriculture within the EU resulting from the dietary changes. Effects in other parts of the food chain (processing, transport, as well as the production of mineral fertilisers) as well as in other regions were not quantified.

Table 4-1: Evaluated alternative human diets and corresponding livestock production

Alternative diet	Human consumption	Livestock production
Reference	Present situation	Present situation
Reference – BF[1]	Present situation	Present situation
–25% beef and dairy	Reduction of beef and dairy consumption by 25%	Reduction in cattle (numbers) by 25%
–25% pig and poultry	Reduction in pig meat, poultry and egg consumption by 25%	Reduction in pig and poultry production (numbers) by 25%
–25% all meat and dairy	Reduction in all meat, poultry and egg consumption by 25%	Reduction in cattle, pig and poultry production (numbers) by 25%
–50% beef and dairy	Reduction in beef and dairy consumption by 50%	Reduction in cattle (numbers) by 50%
–50% pig and poultry	Reduction in pig meat, poultry and egg consumption by 50%	Reduction in pig and poultry production (numbers) by 50%
–50% all meat and dairy	Reduction in all meat, poultry and egg consumption by 50%	Reduction in cattle, pig and poultry production (numbers) by 50%

[1] BF = balanced (nitrogen) fertilisation: fertilisation according to crop requirements / recommendation

4.2.2 Alternative diets

We used statistics compiled by the United Nations Food and Agriculture Organization (FAO) to determine the quantity of commodity used by each EU Member State food system in 2007 (FAO, 2010). These data represent the national supply. The commodities were aggregated into 12 major commodity groups. However, not all the food commodities supplied for human consumption are eaten, as part of the commodity is not edible (e.g. bones, peelings) and losses occur in processing, retail, and in food preparation (FAO, 2010). Information about these food commodity losses were obtained from the literature (Kantor, 1997; Quested and Johnson, 2009). An alternative approach to determining food losses was also taken by comparing FAO supply data with country studies that monitor actual food intake (Elmadfa, 2009). The two approaches yielded similar estimates of the relationship between supply and intake. This study is based on data for commodities as they enter the post-farm human food chain so that a 50% reduction in the weight of eggs consumed, for example, is a 50% reduction in directly consumed eggs and in eggs in processed food products such as bakery products and pasta.

The contrasting effects of ruminant and monogastric-based livestock production on resource use and the environment were expressed in the alternative diets we examined. The production of pig meat, poultry meat and eggs is based almost entirely on cereals and soy bean meal, while Europe's grasslands are a major source of feed for beef and dairy production. In addition, the literature on the life-cycle assessment of commodities consistently shows that monogastric meats have smaller carbon footprints compared with beef. The 50% level of reduction was chosen because it was expected to reveal the overall response of the system and our expectation that a 50% reduction in livestock product consumption would align reasonably well with public health guidelines. The maintenance of 50% livestock products in the food system also enables the food system to easily accommodate variations in dietary requirements within the population.

We assumed that the reduced intake of meat, dairy and eggs is compensated by increased intake of cereals on a food calorie intake basis. If the protein intake dropped below the recommended level, pulses (which are high in protein) were added to the scenario diet. The calculations were carried out for each EU Member State and aggregated to the EU27 level. Consumption reductions were not uniformly applied across all countries. For countries that currently have a low consumption of meat and dairy, consumption was not reduced below the mean EU consumption in the alternative diet. To prevent national consumption being reduced below the level of the mean EU consumption while still achieving the overall reduction in the EU, reductions for other countries were in some cases higher. The consumption of sheep and goat meat is maintained at current levels in our alternative diets because of their particular role on the management of extensive grasslands, which often have high biodiversity values. Also the consumption of fish was assumed to remain at the same level. FAO consumption data were used for the quantification of the intake of saturated fats, calories and proteins as well (Westhoek et al., 2011).

4.2.3 Livestock production, feed use and land use

The assumption was made that a reduction in meat, dairy and egg consumption within the EU has a proportional effect on livestock production within the EU. With fewer livestock, less animal feed is required. We derived data on current feed use from CAPRI (Lesschen et al., 2011; Weiss and Leip, 2012; Leip et al., 2014). The feed calculations were done at the country level and aggregated to the EU27 level (Lesschen et al., 2011). A proportional reduction over the four main feed components (protein-rich feed, energy-rich feed cereals, roughage and forage maize) was applied. These reductions were based on the energy content of the different feeds and adjusted as needed to compensate for a too high or too low N (protein) content of the total feed basket. All calculations were done per animal category and per country. Within these main animal feed component categories, the total use of domestic by-products was maintained. Consequently, imports such as soybean meal were reduced more than proportionally. Within the 'roughage' component, it was assumed that priority would be given to the production of roughage from permanent grassland, therefore reducing the need for arable land or temporary grassland for forage production.

4.2.4 Land use scenarios

The substantial change in the demand for feed results in a net reduction in land needed for the European food system, opening up opportunities to use land for other purposes. We examined the effects of the alternative use of this land using two contrasting land-use scenarios: high prices and greening. The high prices scenario assumes a high global demand for food commodities and an agricultural sector geared to produce and export as much cereal as possible. This means that cropland presently used for forage, e.g. forage maize, temporary grassland and part of the fertilized permanent grassland no longer needed for feed production is converted into arable land for cereal production. The greening scenario assumes that arable land previously used for the production of animal feed, e.g. feed wheat and forage maize, and temporary grassland is converted to perennial bioenergy crops such as canary reed grass, switchgrass, miscanthus, poplar or willow, depending on the location. All permanent grassland is maintained and N fertilisation is reduced to a level commensurate with the lower production level required, resulting in lower N emissions and increased biodiversity.

4.2.5 Nitrogen cycle and greenhouse gas emissions

The changes in livestock numbers, feed and land use were fed into the MITERRA Europe model. MITERRA-Europe is an environmental impact assessment model that calculates emissions of N as nitrous oxide (N_2O), ammonia (NH_3), nitrogen oxides (NO_x) and nitrates (NO_3) and greenhouse gases as carbon dioxide (CO_2), methane (CH_4) and N_2O on a deterministic and annual basis using emission and leaching factors (Lesschen et al., 2009; Velthof et al., 2009). MITERRA-Europe is partly based on data from the CAPRI (**C**ommon **A**gricultural **P**olicy **R**egionalised **I**mpact) (Britz and Witzke, 2012) and GAINS (**G**reenhouse gas-**AI**r pollution **IN**teraction and **S**ynergies) (Klimont and Brink, 2004) models, supplemented with an N leaching module, a soil carbon module and a module for mitigation measures. Input data consists of activity data (e.g. livestock numbers, crop areas), spatial environmental data (e.g. soil and climate data) and emission factors (IPCC and GAINS). The model includes measures to mitigate greenhouse gas and NH_3 emissions and NO_3 leaching.

The reference year is 2004, which is the base year currently used by CAPRI. All the statistical input data are based on three-year averages of the 2003–2005 period. The main input data for MITERRA-Europe are crop areas, animal numbers and feed use at the NUTS-2 (county or provincial) level. Data on crop areas and feed use were taken directly from CAPRI and are based on Eurostat statistics. Data on animal populations relate to countries and were obtained from GAINS. The livestock population was distributed over the NUTS-2 regions according to CAPRI livestock data. Data on annual N fertiliser consumption were collected from FAOSTAT.

4.2.6 N flows

Country-specific N excretion rates of livestock were obtained from the GAINS model (Klimont and Brink, 2004). The total manure N production was calculated at the NUTS-2 level using the number of animals and the N excretion per animal, then correcting for N losses in housing and storage. Manure was distributed over arable crops and grasslands according to Velthof et al. (2009), taking into account the maximum manure application of 170 kg N ha^{-1} from the Nitrates Directive, or a higher application for countries that were granted a derogation. Mineral N fertiliser was distributed over crops relative to their N demand, taking account of the amount of applied manure and grazing manure and their respective fertiliser equivalents (Velthof et al., 2009). The N demand was calculated as the total N content of the crop (harvested part plus crop residue), multiplied by a crop-specific uptake factor, set at 1.0 for grass and perennial bioenergy crops and 1.1 and 1.25 for cereals and other arable crops respectively (Velthof et al., 2009). For the assessment of the alternative diets, balanced N fertilisation (BF) was assumed for mineral fertiliser (Oenema et al., 2007; Velthof et al., 2009). This means that N fertilisation is equal to uptake of the plant during growth, corrected by the crop-specific uptake factor. This approach was justified as the input from animal manure is reduced for the alternative diets; therefore to sustain arable production an increase in mineral fertiliser might be needed. Further N inputs include biological N fixation, which was estimated as a function of land use and crop type (legumes), and N deposition that was derived at NUTS-2 level from the European Monitoring and Evaluation Programme (EMEP).

NH_3 emissions from livestock manure take place during housing, during manure storage, after application to the soil, and from grazed land. Country-specific emission factors and estimates of the efficiency of NH_3 abatement measures were taken from the GAINS model (Klimont and Brink, 2004). N_2O emissions from agriculture consist of emissions from manure storage and from agricultural soils. These latter emissions consist of (i) direct soil emissions after the application of mineral fertiliser and animal manure, and indirect emissions arising from crop residues, (ii) emissions from urine and dung produced during grazing, and (iii) indirect emissions from nitrogen lost in leaching and runoff, and from volatilised and redeposited N. All N_2O emissions were calculated using emission factors from the IPCC 2006 guidelines. The emission factor for NO_x was derived from van Ittersum and Rabbinge (1997) and was set at 0.3% of the N input.

N leaching was calculated by multiplying the soil N surplus by a region-specific leaching fraction, based on soil texture, land use, precipitation surplus, soil organic carbon content, temperature and rooting depth. Surface runoff fractions were calculated based on slope, land use, precipitation surplus, soil texture and soil depth (Velthof et al., 2009).

The effect of reduced NH_3 emissions from agriculture on N deposition was assessed using the GAINS model. GAINS describes the interrelations between these multiple effects and the pollutants (SO_2, NO_x, PM, NMVOC, NH_3, CO_2, CH_4, N_2O, F-gases) that contribute to these effects at the European scale (Amann et al., 2011). The activity data for the selected scenario were provided by national experts, therefore improving the quality of the national input, while other parameters such as emission factors and abatement technology implementation rates were taken from the European scenario. Input data for the activity change in the proposed scenarios were obtained from the MITERRA-Europe model, as described above. The oxidised N deposition and averaged area critical loads exceedance were based on outcomes of the GAINS model.

4.2.7 Greenhouse gas emissions

CH_4 emissions in MITERRA-Europe were derived from European regional livestock numbers and IPCC (2006) emission factors. Changes in land use and land management influence soil carbon (SC) stocks. Following the IPCC (IPCC, 2006) approach, the amount of SC in mineral soils was calculated by multiplying a default reference value by relative stock change factors for land use, soil management and carbon inputs. The reference soil carbon stock is a function of soil type and climate region for the upper 30 cm. IPCC assumes a period of 20 years to reach a new equilibrium for soil carbon stocks. Relative stock change factors were assigned for each crop activity (Nemecek et al., 2005). Changes in soil carbon stocks caused by changes in cropping shares were calculated and divided by 20 years to obtain annual CO_2 emissions. All greenhouse gas emissions are expressed in CO_2 equivalents, based on the latest estimates of the potential 100-year global warming values relative to carbon dioxide (CO_2: 1, CH_4: 25 and N_2O: 298) (IPCC, 2006).

4.3 Results

4.3.1 Dietary changes and effects on human health

We calculated that in diets with a lower consumption of meat, dairy and eggs, the average consumption of cereals increases by 10 to 49% (Table 4-2). The protein intake in the alternative diet is up to about 10% lower compared with the reference (Figure 4-2). Nevertheless, the mean protein intake is still at least 50% higher than requirements as set out by the World Health Organization (WHO) (WHO, 2007). Additional pulses to provide a sufficient supply of proteins were needed in only one alternative diet in one country, i.e. Hungary. In the alternative diets, the intake of saturated fat is reduced by up to 40% (Figure 4-2). This proportion is close to the recommended maximum dietary intake (RMDI) proposed by WHO (WHO, 2003, 2008a, 2011), corresponding to an RMDI for saturated fat of 25.5 g per day in Europe (WHO, 2003). These dietary changes reduce average red meat consumption from the current 89 g per person per day to 46 g (Figure 4-3) in case of 50% reduction of all meat and dairy, bringing it within the recommended maximum intake advised by the World Cancer Research Fund (about 70 g per person per day), equivalent to a population average of 43 g of red meat per person (WCRF and AICR, 2007).

Table 4-2: Average per capita consumption of selected food commodity groups in the reference and the six alternative diets (in g person^{-1} day^{-1})

	Reference	**–25% beef and dairy**	**–25% pig and poultry**	**–25% all meat and dairy**	**–50% beef and dairy**	**–50% pig and poultry**	**–50% all meat and dairy**
Cereals	256	291	283	319	326	311	382
Pulses	4	4	4	4	4	4	4
Dairy (milk basis)	554	416	554	416	277	554	277
Beef	23	17	23	17	12	23	12
Poultry	32	32	24	24	32	16	16
Pig meat	62	62	47	47	62	31	31
Sheep and goat meat	3	3	3	3	3	3	3
Eggs	28	28	21	21	28	14	14

[1] The use of sugar, potatoes, fruit and vegetables and fish is assumed to remain constant and are therefore not presented here.

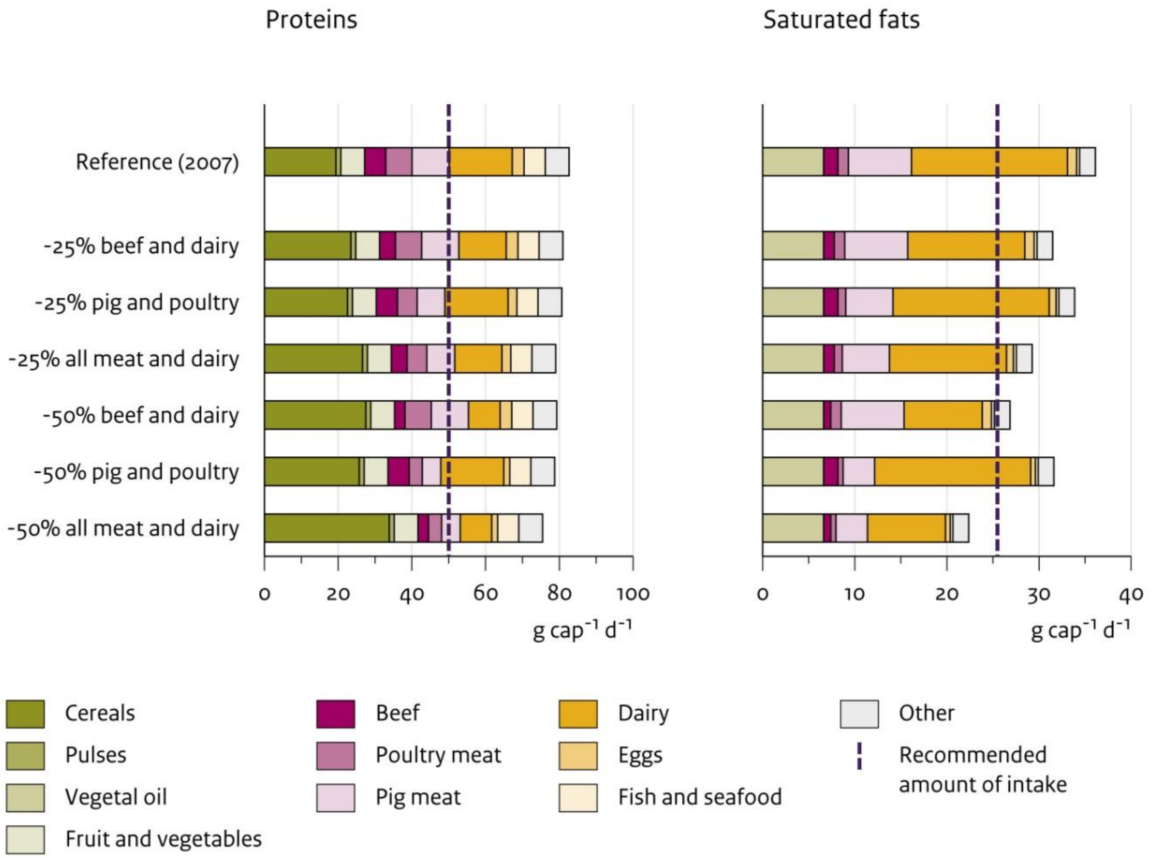


Figure 4-2: Effects of dietary changes on average daily per capita intake of proteins and saturated fats

a. Population average daily protein intake for the EU27 in g day^{-1} from the various food commodity groups in the reference (2007) situation and in case of the six alternative diets in which meat and dairy consumption is stepwise reduced. b. idem, for saturated fats.

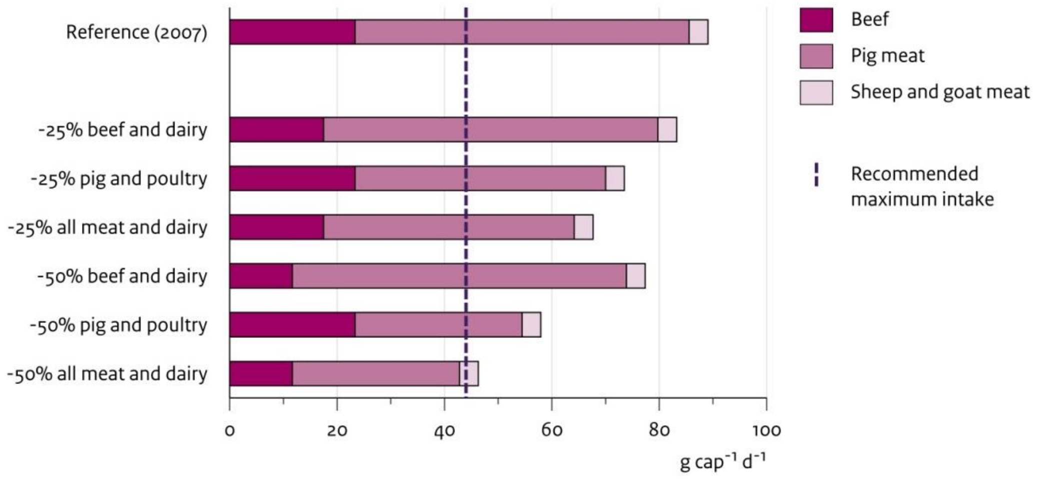


Figure 4-3: Average intake of red meat in the six alternative diets and the reference diet

Significant health benefits are expected from a lower intake of saturated fats and red meat, as diets rich in saturated fat are associated with an increased risk of cardiovascular diseases (CVD) and stroke. In the WHO European region, currently around 25% of total mortality can be attributed to CVD and 15% to stroke, in total about 3.8 million deaths annually (WHO, 2008b). In terms of disease burden, these attributable fractions are around 11% and 6.5% of total annual loss of disability-adjusted life years respectively (DALYs, an aggregate of years of life lost and years spent in reduced health) (WHO, 2008b). There are also indications that the intake of red meat is associated with an increased risk of colorectal cancer (CRC) (Norat et al., 2002; Chan et al., 2011, Pan et al., 2012). The mortality and disease burden of CRC in the WHO European region are substantially lower than the CVD burden (250 000 annual deaths; 2.5% of total mortality; 1.4% of total annual DALYs). The reduction in livestock production and subsequent reduction in emissions may also have indirect health benefits, related to a lower use of antibiotics (Marshall and Levy, 2011) and improved water quality (nitrates) (Powlson et al., 2008) and air quality (related to the role of NH_x in particulate matter formation) (Moldanová et al., 2011).

4.3.2 Effects on feed demand and land use

The reduction in livestock production leads to a reduced demand for feed. The total demand for feed is reduced from the baseline use of ~520 to ~285 Teragram (Tg) in case of a 50% reduction in all meat and dairy production (Table 4-3). The need for forage grown on arable land is reduced by 90% which is the greatest reduction. This is a result of the assumptions which favour forage from grasslands over forage from arable land. The 50% meat and dairy reduction diet gives a 75% reduction in soy meal use, a 46% reduction in energy-rich feed imports and a 52% reduction in feed cereal use. In the diets in which only pig and poultry is reduced, the use of grass, fodder maize and fodder on arable land remains unchanged compared to the baseline. The reduction of cereal use is higher in alternatives with reduction of pig and poultry consumption than in case of reduced beef and dairy consumption.

Table 4-3: Feed use in EU27 in the reference and the six alternative diets (in Tg yr^{-1})*

	Reference	–25% beef and dairy	–25% pig and poultry	–25% all meat and dairy	–50% beef and dairy	–50% pig and poultry	–50% all meat and dairy
Grass	177	159	177	159	121	177	121
Fodder maize	54	42	54	42	30	54	30
Fodder on arable land	59	21	59	21	6	59	6
Whole milk powder	1	1	1	1	0	1	0
Milk for feeding	2	1	2	1	1	2	1
Cereals	145	132	121	107	119	96	70
Cassava	2	1	1	1	1	1	1
Corn gluten feed	4	4	3	3	4	2	2
Molasses, import	2	2	2	2	2	1	1
Other protein-rich feed	26	26	26	26	26	26	25
Soybean meal	30	25	24	19	20	17	7

*The use of other feed categories remains constant (domestic molasses, straw, other feed, fodder roots).

As the demand for animal feed declines, land currently used for feed production will become available for alternative purposes. In the high prices land-use scenario, 9.2 million hectares of mainly intensively managed permanent grassland and 14.5 million hectares of arable land are no longer required for feeding European livestock where there is a 50% reduction in all meat and dairy production (Table 4-3, Figure 4-4). This land is instead used for additional cereal production, leading to an increase in the EU cereal acreage from 60 to 84 million hectares and an increase in the net export of cereals from 3 to 174 Tg. In the greening land-use scenario, around 14.5 million hectares are cultivated with perennial energy crops.

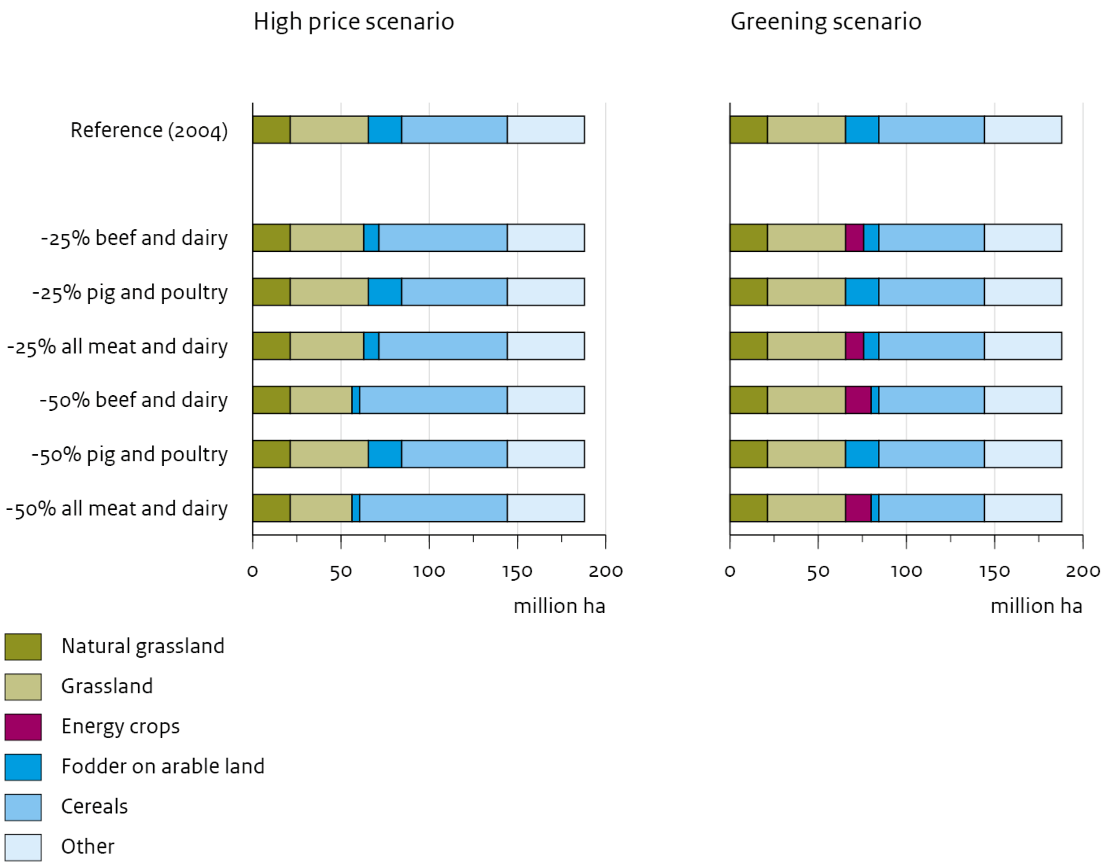


Figure 4-4: Agricultural land use in the EU (in million hectares) in the reference (2004) and the six alternative diets and two land use scenarios

The demand for food cereals increases when the consumption of meat and dairy is reduced, but the demand for feed decreases more (Figure 4-5). In combination with the availability of new land for cereal production, the domestic cereal production becomes much larger than the domestic demand, leading to an increase in cereal exports. As a consequence of the dietary changes, the average amount of cropland used within the EU for domestic food production is reduced from 0.23 hectare to 0.17 hectare per EU citizen.

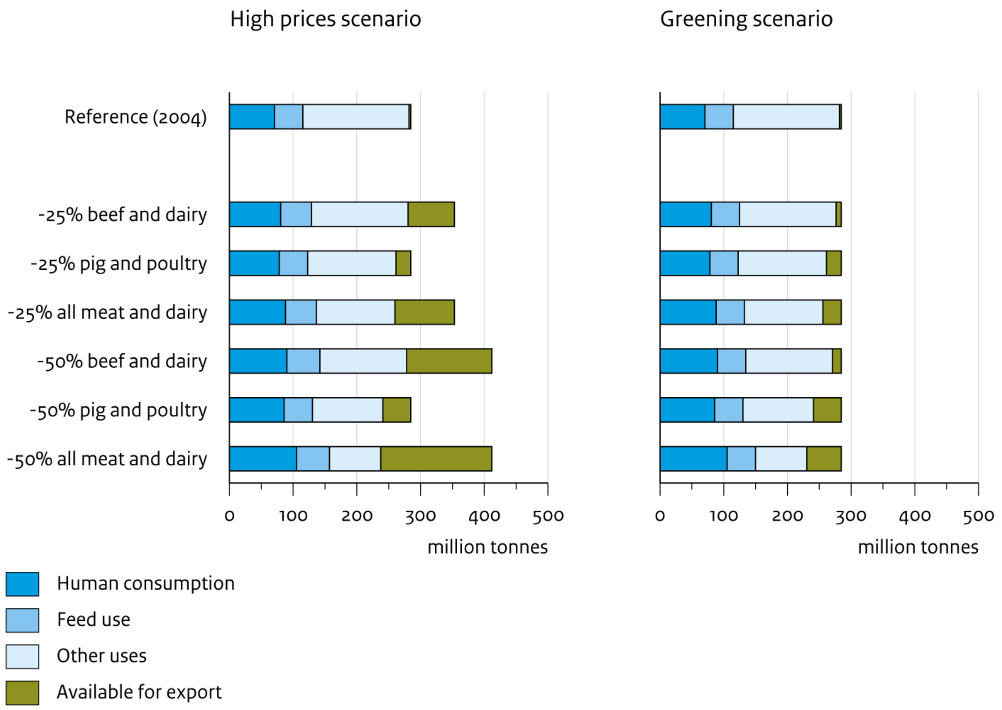
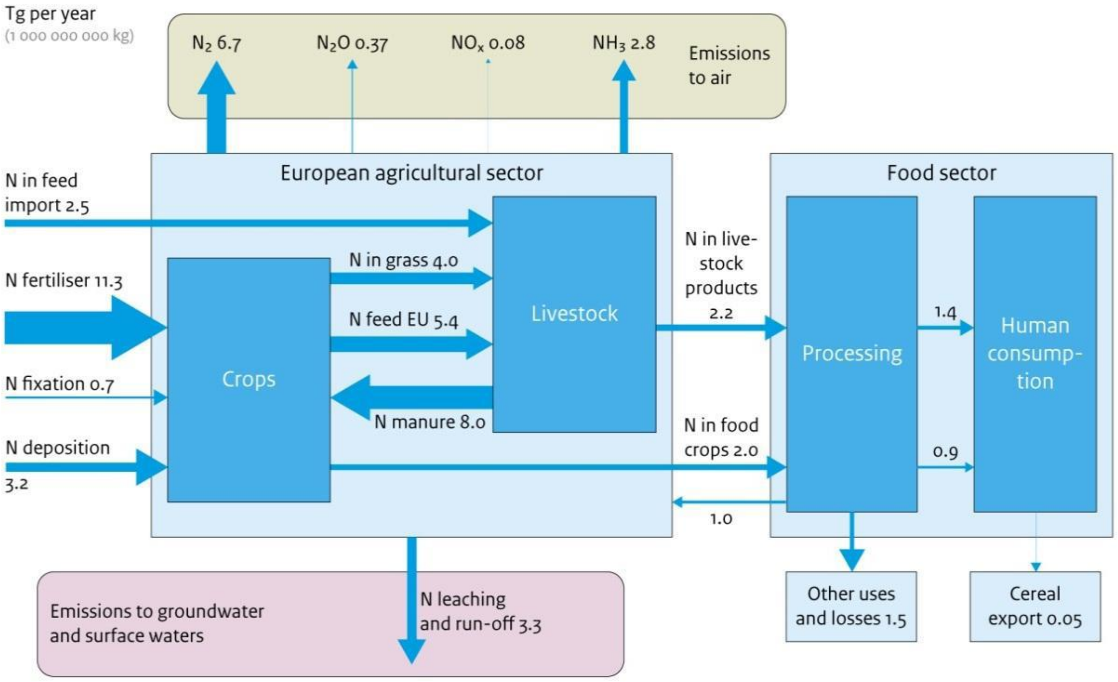


Figure 4-5: Cereal demand in the EU for different alternative diets and two land use scenarios

4.3.3 Effects on reactive N emissions

A reduction in livestock production leads to a significant decrease in reactive N inputs and losses across Europe (Figure 4-6). In the greening scenario in combination with the 50% reduction of all meat and dairy, the fertiliser input is reduced from 11.3 to 8.0 Tg N yr^{-1}, while emissions of nitrates to ground and surface waters and NH_3 to air are both reduced by 40% compared with the reference situation. The N use efficiency of the EU food system as a whole improves from 22% in the reference situation to 41% under the greening scenario and to 47% under the high prices scenario. The N use efficiency is here defined as the N output in food crop and livestock products as a percentage of the total N input (Oenema et al., 2009).

Nitrogen flows in agricultural foodsystem in EU27, reference 2004 based on Miterra data



Nitrogen flows in agricultural foodsystem in EU27, -50% all meat and dairy Greening scenario

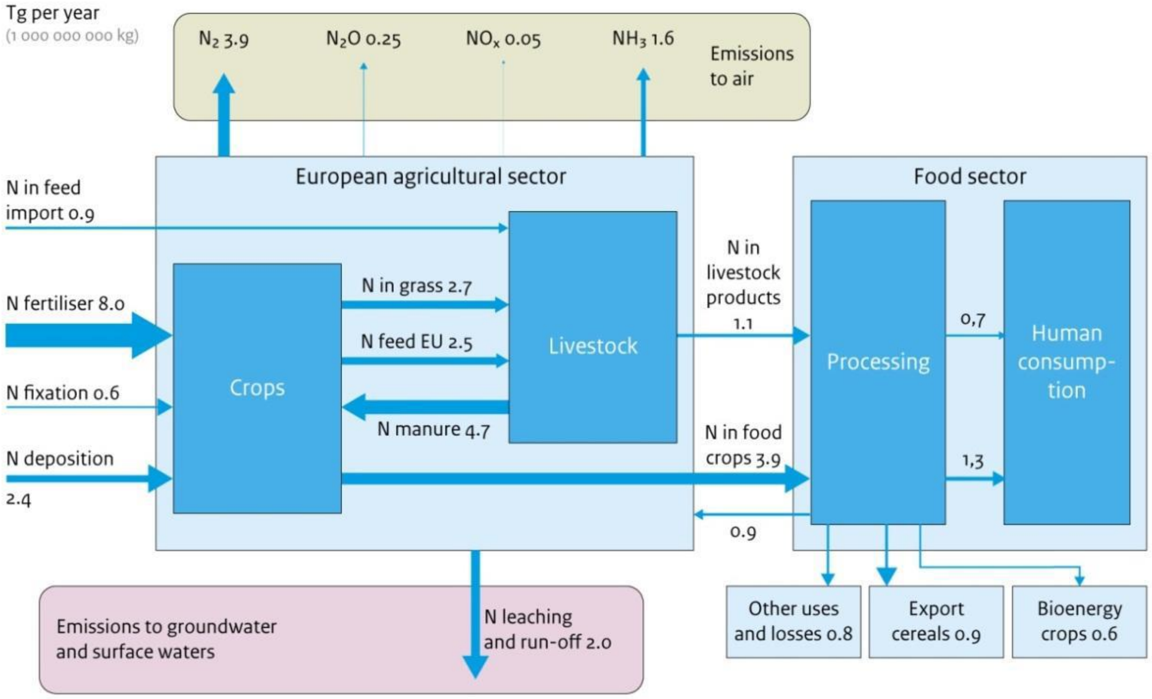


Figure 4-6: Nitrogen flows (in Tg yr^{-1}) in the EU agricultural and food system in the reference situation for 2004 (a) and in the case of the alternative diet with a 50% reduction in consumption of meat, dairy and eggs in the *greening land use* scenario (b)

The results indicate that at the current level of livestock production, changes in the emissions of reactive N from European agriculture are, at EU scale, closely related to relative changes in the magnitude of livestock production. Reducing N emissions through dietary change leads to a cascade of positive effects (Galloway et al., 2008). The reductions in reactive N leaching, NH_3 emission and deposition are the highest in regions with intensive livestock production. Under the 50% diet, average NH_3 emissions and NH_x deposition in the EU are reduced by about 40%, resulting in a reduction in the exceedance of critical load thresholds for adverse Nr effects on ecosystems (Figure 4-7). Reduced nitrogen emissions will lead to an improvement in water quality and lower eutrophication risks. The total N load to rivers and seas for the EU27 in 2005 was estimated at 4.6 Tg, of which 55% was from agricultural sources (Grizzetti et al., 2012). Due to human activities, nitrate concentrations in major European rivers have increased by as much as a factor of ten during the 20th century. Although improvements have been made in recent decades, the eutrophication threshold value for nitrate in freshwater and marine systems is commonly exceeded. Similarly, the WHO nitrate standard for drinking water (50 mg per litre) is commonly exceeded in shallow phreatic groundwater (van Grinsven et al., 2012).

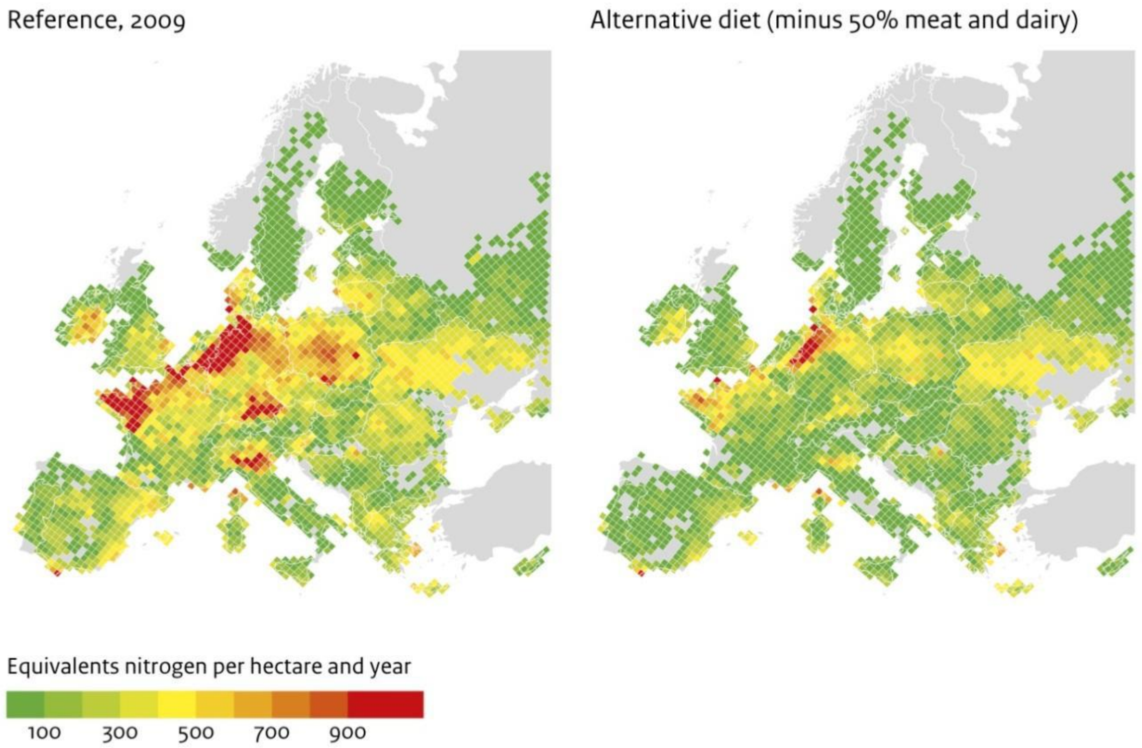


Figure 4-7: Annual exceedance of critical load for N deposition in kg N per hectare for natural ecosystems for the reference and 50% less meat and dairy alternative diet under the *high prices* land-use scenario.

4.3.4 Effects on greenhouse gas emissions

Net greenhouse gas emissions directly related to EU agricultural production (excluding pre-farm and post-farm emissions) decrease by 42%, from 464 to 268 Tg CO_2e yr^{-1} in the case of minus 50% all meat and dairy in combination with the *greening* scenario (Figure 4-8). In the *high prices* scenario, net greenhouse gas emissions decrease by 19% to 374 Tg CO_2e yr^{-1}. Reductions in CH_4 emissions are similar in the two scenarios as these are directly coupled to the number of ruminants, and these form the largest component of the greenhouse gas emission reduction (108 Tg CO_2e yr^{-1}). N_2O emissions are reduced to a lesser extent because they are mainly linked to reactive N turnover processes in soils that are associated with both livestock and arable farming. In the high prices scenario, tillable grasslands in the EU are converted into arable land, leading to additional CO_2 emissions from decreasing soil carbon stocks. These emissions contribute 59 Tg CO_2e yr^{-1}, when averaged over a period of 20 years. In the greening scenario, soil carbon sequestration occurs as the perennial biomass crops increase levels of carbon in the plant-soil system equivalent to 36 Tg CO_2e yr^{-1}, again averaged over 20 years. Reductions in emissions outside the EU, related to the lower demand for soybean and the higher export of cereals, were not included in our calculations but would provide a substantial additional benefit (Stehfest et al., 2013). The yearly amount of biomass for energy produced in the greening scenario represents 2.3 exajoule or 54.1 Tg oil equivalent, equal to roughly 3% of Europe’s current primary energy intake (Eurostat, 2011).

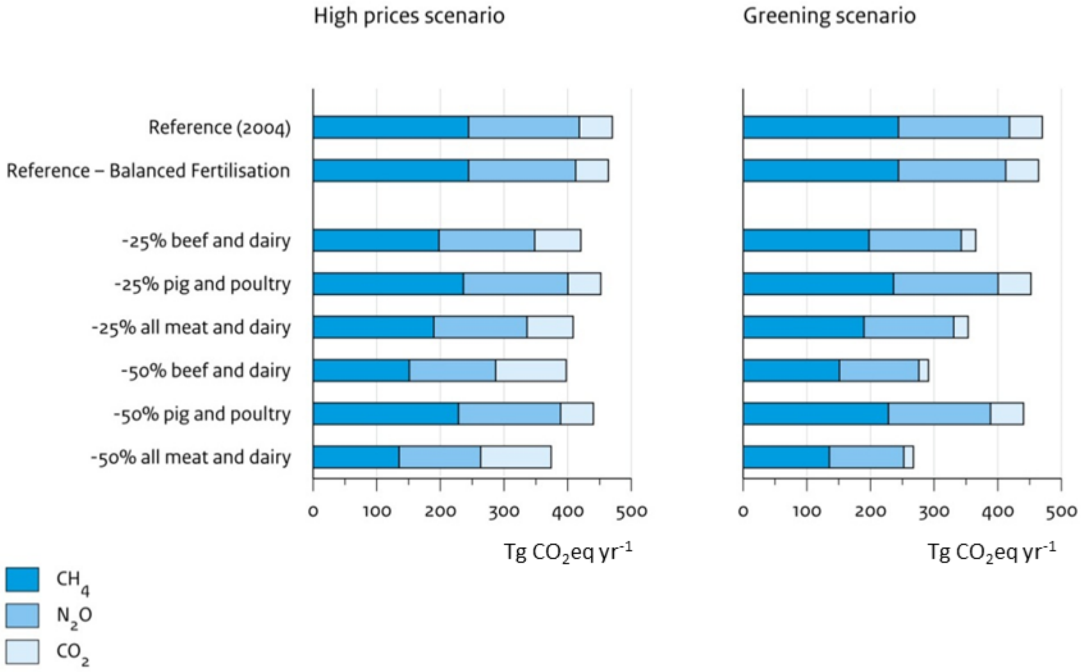


Figure 4-8: Greenhouse gas emissions (in Tg CO_2e yr^{-1}) from EU agriculture in the reference situation and the six alternative diets for the high prices scenario and the greening scenario

4.4 Discussion and conclusion

Our study explored the consequences for human health and environment of replacing 25 -50% of the current meat, eggs and dairy consumption in the EU with plant-based food, assuming that consumption and production of livestock products in Europe remain tightly linked. Reducing livestock production by 50% will lead to large structural changes within the EU agricultural sector resulting in a reduction in emissions of greenhouse gases (of 25-40%) and reactive N (around 40%). Due to reduced feed demand, use of imported soybean meal would drop by 75% and the EU would become a large net exporter of basic food commodities. Given increasing global food demand, the beneficial environmental effects of dietary changes within the EU would therefore extend beyond its territory. The results reflect the large share of livestock production in the total environmental impact of EU agriculture, as was already revealed for greenhouse gases by Lesschen et al. (2011) and for N by Leip et al. (2014).

In order to be able to perform this study, we made a number of important assumptions. The first assumption is that the lower meat, eggs and dairy intake is compensated by a higher cereal intake while maintaining total dietary energy intake. As far as health impacts are concerned, this is a relatively conservative approach. First of all, the current average per capita energy intake is higher than is needed. Full caloric replacement of livestock products is therefore not necessary. Second, additional health benefits could be expected if this energy replacement were to be partly in the form of fruit and vegetables, since in most European countries the average intake of these is currently below the recommended level (Elmadfa, 2009). As far as environmental impacts are concerned, substitution of the energy with other carbohydrate rich commodities (e.g. potatoes) and pulses yield similar effects as substitution with wheat on greenhouse gas emissions and land use, while substitution of substantial amounts of energy using fruit and vegetables would lead to smaller environmental benefits compared with the currently applied alternative diets. This is because in general the environmental effects (as land use and greenhouse gas emission per calorie) of fruit and vegetables are higher compared to those of cereals but are lower compared to those of dairy and meat (Garnett, 2013; Nemecek and Erzinger, 2005; Nemecek et al., 2005). We did not investigate the effects of the dietary changes on the intake of micro-nutrients. As the current intake of for example calcium and iron is already low in most EU countries (Elmadfa, 2009), this is certainly an aspect that requires further attention. In all diets, the average protein intake in the EU remains higher than requirements. Even with a 50% reduction in all animal products, the mean EU intake of proteins is still more than 50% higher than requirements.

The second important assumption is that the reduction in meat, eggs and dairy consumption is followed by a parallel reduction in livestock production within the EU, meaning that the current tight link between production and consumption in Europe will be maintained. Instead of reducing production, EU farmers and food industry could try to compensate for reduced domestic markets by increasing exports to other countries. If this happened, the environmental benefits of the consumption change would largely shift from within to outside the EU. As current production costs of many livestock products (except for potentially dairy products) are higher in the EU than in some other countries, such as in Brazil, Australia, The United States of America and Thailand, it is unlikely that the EU will become a significant net exporter of livestock products, as also indicated by the assessment of similar scenarios by using economic models (Stehfest et al., 2013).

No explicit sensitivity analyses were performed, although the combination of dietary and land use scenarios can be considered as a kind of sensitivity analysis. The results of these alternatives show clear, plausible and largely linear outcomes for environmental effects. Previous research showed that the uncertainty in the absolute emission estimates as calculated by MITERRA-Europe is relatively small at EU-scale due to cross-correlations and spatial aggregation (Kros et al., 2012). Uncertainty for the relative changes in emissions between the various alterative diets and scenarios will be even lower. The most sensitive parameter for the reactive N and greenhouse gas emissions will be the assumed alternative land use.

As stated in the methodology section, only biophysical models were used. Would the use of economic models have yielded different outcomes? And would it be possible to assess the economic effects on the agricultural sector and other economic sectors of these dietary changes?

Other studies (for example Stehfest et al., 2013 and Lock et al., 2010) have assessed the environmental and economic impact of reduced meat and dairy consumption using economic models. It is clear from these studies that the use of economic models is not straight-forward and is not as transparent as our approach for two reasons. First, there is the effect of the choice of model to consider (Stehfest et al., 2013). Computable general equilibrium (CGE) models includes all sectors, but usually have less detail, whereas a partial equilibrium model (PE) only represents one sector (the agricultural sector) and where everything has to be solved within this sector. The PE models come up with different answers than CGE models, as within CGE models labour and other production factors can move from one sector to another sector. Second, in order to force the models to simulate reduced consumption of meat and dairy, consumption functions need to be altered. In the approach taken by Lock et al. (2010), who assessed the effects for two countries, assumptions regarding the effect on trade had to be made. Stehfest et al. (2013) also showed that the results largely depend on how trade and trade policies are modelled.

The effects on the livestock sector will most likely be severe, especially if the consumers' preferences change rapidly. This is demonstrated by a study of the United Kingdom food system using scenarios similar to ours. Audsley et al. (2010) showed that the reduction in the UK farm gate value of livestock from dietary change is not compensated by the increase in the value of crops for direct human consumption. Their study highlighted strong regional effects with gains in areas with high quality arable land and losses of income on less capable land in Scotland and Wales in particular. However, if the attitude towards food within society changes and people would opt for products with higher added value, as meat and dairy produced with higher animal welfare, the economic effects on the livestock sector would be less severe. The farm-level economic impact of a change along these lines depends crucially on what replacement output is found for the land released from livestock production.

Our study shows that a change towards diets with lower consumption of livestock products has clear environmental and health benefits. But this still leaves the question: is it realistic to consider such consumption changes? Consumer preferences may change due to environmental or health concerns, or simple because eating meat and dairy would become less 'normal' or fashionable for various reasons (Dagevos and Voordouw, 2013), a process that is already happening. A trend could be actively 'nudged' by governments, food manufacturers, retailers and food service acting together to stimulate change.

A more directive approach would be to make meat and dairy products more expensive, either by direct taxes, or by taxing the environmental effects (as emissions of greenhouse gases and nutrients) of their production. As meat and dairy have larger environmental footprints, the price of animal products would increase stronger than that of the plant-based products. It is doubtful whether such a measure would be widely accepted. The same effect of rising prices might occur due to changes in global prices for livestock products as global demand increases. A reduction in meat and dairy production within the EU in response to reduced demand because of high global prices is less plausible.

This study is one of the first to examine in detail the relationships between diet-led changes in food production and continental-scale effects on land use, the N cycle, greenhouse gas emissions and the associated implications for human health. It demonstrates that dietary changes can produce a cascade of effects, through reduced livestock and manure production, lower feed demand, resulting in lower N and greenhouse gas emissions, and freeing up agricultural land for other purposes. At least in Europe, the evidence that diet is important for environmental policy has already impacted the policy community. The Roadmap to a Resource-Efficient Europe (COM, 2011) highlights the food sector as priority area for developing incentives for healthier and more sustainable production and consumption of food. Moving in this direction requires attention be given to stimulating the change required and checking for any unintended nutritional consequences. The biggest challenge is for agricultural policy in Europe: how to progress such a fundamental change in European agriculture and address the implications for farm incomes, farmed landscapes, and planning at a wide range of scales.

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5 Integrated assessment of diet shifts in Germany

This chapter was submitted as Susanne Wagner, Jan-Peter Lesschen, Oene Oenema: Integrated assessment of diet shifts in Germany. Agriculture, Ecosystems and the Environment (under review).

Abstract

Livestock production covers 65% of agricultural land and causes a major share of emissions in Germany, while the consumption of livestock products is higher than recommended in healthy eating guidelines. This study investigated the impacts of a 50% reduction in livestock production and consumption, compensated by vegetable food on a dietary energy base, on land use and on emissions of ammonia, particulate matter and greenhouse gases, in Germany. Three scenarios explored the potentials of the freed-up land for (i) food supply with additional cereal production for export, (ii) lignocellulosic biomass supply for energy and material use and (iii) biodiversity conservation and related emissions with the biophysical model MITERRA. The diet shift freed up 2.5 million hectares of cropland (23%) and 1.6 million hectares of permanent grassland area (33%) in Germany. Cultivating cereals produced 22 million tons for export that could feed 55 million people additionally. Cultivating perennial lignocellulosic biomass for energy use produced 550 petajoule of heat energy, contributing 37% to Germany’s renewable energy target in 2020, but would be outcompeted by wind towers that produce the same amount of energy on about 10% of the area. The alternative use as raw material for the production of bulk chemicals and bioplastics could meet the future demand for biomass to replace fossil based materials in a bioeconomy. Biodiversity conservation was ensured by extensifying grasslands instead of grassland conversion and turning arable land into fallows. Emissions of ammonia were reduced by up to 45%, of particulate matter by up to 38% and of greenhouse gases by up to 40%. The external costs, based on the integrated assessment model EcoSense, increased in the food supply scenario with increasing cereal production and decreased in the lignocellulosic biomass supply scenario and the biodiversity conservation scenario with the production of lignocellulosic biomass, the extensification of grasslands and fallow land. The agricultural sector income was reduced by 2-9% (700-3,000 million EUR) and redistributed from the livestock sector to the arable sector. It can be concluded that a diet shift can have large impacts on land use and on emission reduction. The results of the land use scenarios indicate that the freed-up arable land be used for food production and lignocellulosic biomass production and that grassland be maintained for biodiversity conservation.

Key words: Livestock product consumption, ammonia, particulate matter, greenhouse gases, food supply, lignocellulosic biomass, biodiversity, bioeconomy

5.1 Introduction

With growing global population and the transformation from a fossil based economy to a bio-based economy, as intended by the European Union, greater use of renewable biological resources is a necessity. Concerns exist about the competing use of biomass due to land scarcity and the potential impacts on food supply and the environment caused by the growing demand for biomass for material and energy use (European Commission, 2012). Livestock production uses 30-75% of harvested biomass at the global level and occupies 80% of anthropogenic land use (Krausmann et al., 2008; Stehfest et al., 2009) and is thus in direct competition with crop production for human consumption and with potential alternative land uses such as non-food biomass production or nature conservation. Moreover, livestock production is the main driver for increasing land use by agriculture (Kastner et al., 2012). With shifts to intensive cereal feeding and increasing meat consumption due to economic growth, land demand is likely to increase much more than expected (Keyzer et al., 2005). In Germany, livestock production covers 10.8 million hectares (ha) (65%) of agricultural land, thereof 4.8 million ha of permanent grassland (BMELV, 2010). Besides anthropogenic land use, agriculture, particularly livestock production, is the major contributor to ammonia (NH_3) emissions and causes also emissions of fine particulate matter ($PM_{2.5}$) and of greenhouse gases. In Germany in 2014, the agricultural sector emitted about 95% of NH_3 (704 Gigagram [Gg]), 8% of $PM_{2.5}$ (8 Gg) and 8% of greenhouse gases (66 Teragram [Tg] in carbon dioxide equivalents [CO_2e]). 68% of NH_3 emissions, 92% of $PM_{2.5}$ emissions and 53% of greenhouse gas emissions originated from livestock production (Umweltbundesamt, 2016).

The implications at the global level are serious. Agricultural expansion into natural ecosystems affects biodiversity and, by reducing carbon sequestration, the climate (Steinfeld et al., 2006). NH_3 emissions impair terrestrial biodiversity via nitrogen deposition and can form secondary aerosols that are part of the $PM_{2.5}$ fraction causing respiratory and cardiovascular diseases and a reduction in live expectancy in humans (Brunekreef and Holgate, 2002; Krupa, 2003). Greenhouse gas emissions cause climate change (IPCC, 2008).

Environmental policies demand the reduction of air pollutants such as NH_3 and $PM_{2.5}$ and of greenhouse gases as well as the halt of biodiversity loss (European Commission, 2008; European Communities, 2001, 2006, 2008; UNECE, 2013). Furthermore, the Common Agricultural Policy (CAP) reform 2014-2020 demands sustainable agricultural production. Meeting these targets will require substantial emission reductions and efforts for environmental protection that may include a reduction in livestock production.

Plant-based food items need less land and cause less greenhouse gas and nitrogen emissions than livestock products (Leip et al., 2014; Carlsson-Kanyama and González, 2009; Gerbens-Leenes et al., 2002; Goodland, 1997; Reijnders and Soret, 2003). Consequently, human diets with low livestock product consumption need less land than diets rich in livestock products (Gerbens-Leenes and Nonhebel, 2002; Peters et al., 2007; Westhoek et al., 2014; Wirsenius et al., 2010a). Furthermore, such diets reduce greenhouse gas and nitrogen emissions and subsequent environmental impacts and may have higher reduction potentials than technical measures (Audsley et al., 2010; Friel et al., 2009; McMichael et al., 2007; Popp et al., 2010; Stehfest et al., 2009; Westhoek et al., 2014; Garnett, 2009, 2011). In integrative studies, diets rich in plant-based food products simultaneously benefit the climate, biodiversity conservation, the supply of land, water and energy, and human health (Aiking, 2011; Boer et al., 2006; Tukker et al., 2011).

Besides the environment and indirect health effects, livestock product consumption also affects human health directly. A reduction in livestock product consumption can reduce health risks such as cancer and heart diseases (Friel et al., 2009; Friel et al., 2011; McMichael et al., 2007; Westhoek et al., 2014). The livestock product consumption in Germany is higher than recommended in healthy eating studies (Max Rubner-Institut, 2008; McMichael et al., 2007; Lanou, 2009). These findings indicate that a shift from animal-based to plant-based food consumption may also be beneficial for human health.

This study investigated the impacts of a 50% reduction in livestock production and consumption on land use, on emissions of NH_3, $PM_{2.5}$ and greenhouse gases, on soil carbon sequestration and on biodiversity in Germany and developed scenarios for the alternative use of land freed up from livestock feed and fodder production. The environmental impacts were analysed with the biophysical model MITERRA and complemented by an economic analysis of external costs based on the integrated assessment model EcoSense and of economic impacts on the agricultural sector. In Germany, livestock consumption was higher than recommended and livestock production covered a high share of agricultural land and was a major contributor to environmental impacts of agriculture. We reasoned that a reduction in livestock production and consumption would free up land currently cultivated with livestock feed or fodder that could alternatively be used for food production, non-food biomass production or nature conservation and would reduce emissions of NH_3, $PM_{2.5}$ and greenhouse gases. Such a diet shift could simultaneously contribute to air quality control, climate change mitigation and biodiversity conservation as well as to the supply of food and non-food biomass and reduce the competition for land in a bioeconomy.

5.2 Method

5.2.1 Overview on scenarios for food consumption, livestock production and land use

Explorative scenarios for food consumption, livestock production and land use were developed. Impacts of less livestock product consumption and production on land use and atmospheric emissions and their implications on human health and terrestrial biodiversity were analysed. Finally, economic impacts on external costs and on the agricultural sector were estimated. It was assumed that the consumers voluntarily changed their food consumption patterns towards a diet containing 50% less animal-based food products. Further, the reduction of livestock product consumption in human diets would be compensated by plant-based food consumption on a dietary energy basis. The changes in food consumption patterns would translate into proportional changes in agricultural and livestock production in Germany, while the degrees of self-sufficiency remained unchanged (BMELV, 2010). The decrease in livestock numbers would lead to a decrease in livestock feed and fodder requirements. The area freed up from feed and fodder production would exceed the area increase for additional plant-based food production, resulting in a net release of land. Scenarios for the alternative use of freed-up land were developed. All scenarios were compared against a projection of the food consumption and agricultural and livestock production in Germany to the year 2020 included in the MITERRA model, which served as a reference scenario (Blanco Fonseca et al., 2010).

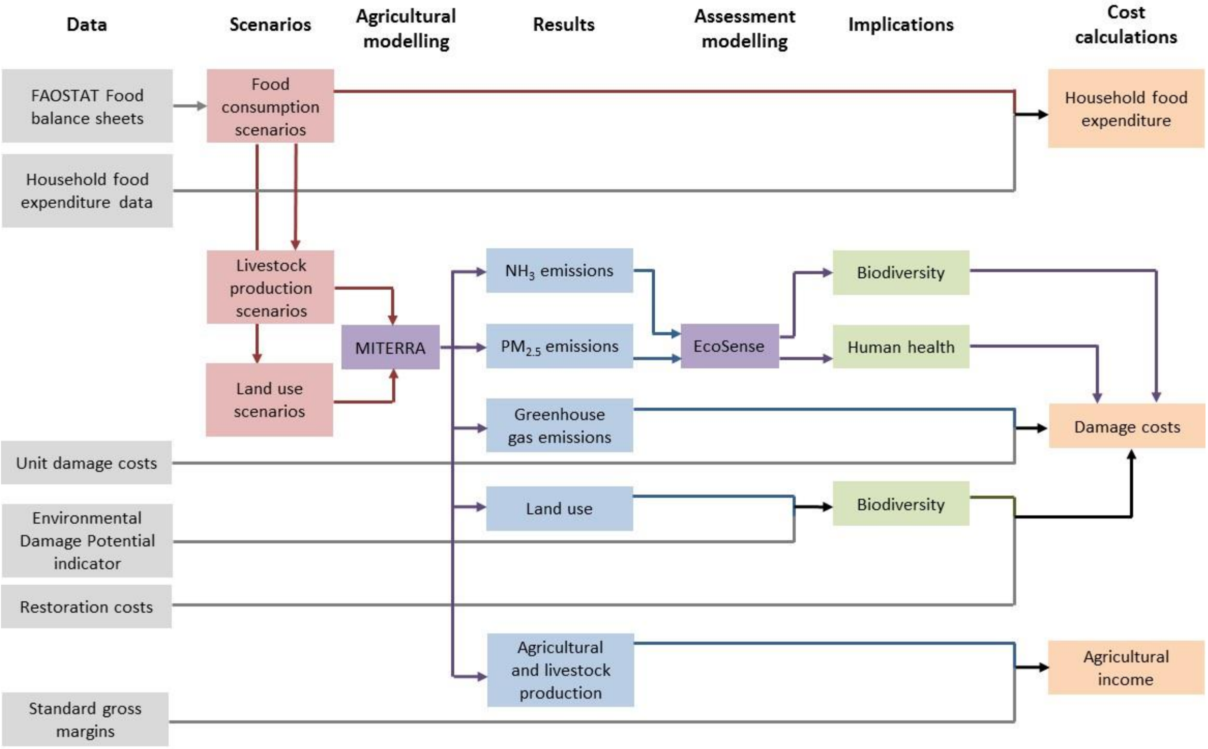


Figure 5-1: Overview of the approach and data flows to analyse food consumption, livestock production and land use scenarios and their impacts on the environment and on economic aspects

The livestock production and land use scenarios were implemented into the MITERRA model (Figure 5-1). MITERRA is a biophysical model that calculates annual nutrient flows and greenhouse gas emissions including soil carbon from agriculture in the EU on a deterministic basis (Velthof et al., 2009; Lesschen et al., 2011). Its main input data are crop areas, livestock distribution, feed inputs (derived from the CAPRI model Britz and Witzke, 2012) animal numbers, excretion factors, ammonia (NH_3) emission factors (derived from the GAINS model Klimont and Brink, 2004), crop yields, fertiliser consumption, animal production (from FAO statistics) and emissions factors for greenhouse gases (from IPCC). The MITERRA model analysed scenario impacts on land use and on emissions in Germany. The impacts of air pollutants on human health and on terrestrial biodiversity via nitrogen (N) deposition as well as associated external costs were estimated based on calculations of the integrated environmental assessment model EcoSense (Bickel and Friedrich, 2005; Krewitt et al., 1995). Following the impact-pathway-chain, EcoSense tracks air pollutants starting from their source along their dispersion and conversion in the atmosphere to the impacts on receptors and, by valuating these impacts, derives external cost estimates.The impacts and external costs of land use change on biodiversity and of greenhouse gas emissions as well as the economic impacts on the agricultural sector and on private households based on literature analysis (see chapters 5.2.5 and 5.2.6).

5.2.2 Food consumption scenarios

It was assumed that the livestock product consumption in human diets was reduced by 50%. Three scenarios were defined: One scenario contained a reduction in beef and dairy products; another analysed a reduction in pork, poultry and eggs, and in the third scenario, the two approaches were combined. No changes in the consumption of sheep and goats were assumed, because their share is less than 1% of total food consumption and thus considered negligible (BMELV, 2010). The reduction in livestock product consumption was compensated by a linear increase in the consumption of cereals, potatoes, vegetables, fruits and pulses on energy base, i.e., the energy supply per capita remained constant. It was assured that the protein supply was still in line with healthy eating recommendations. The food consumption pattern was adjusted based on food supply data from the FAOSTAT food balance sheets (FAO, 2012). The food balance sheets contain data on production quantities, imports and exports at commodity level. They estimate the amount of food supply per capita per day and provide information on total energy, protein and fat availability for each commodity. The food supply data were projected to the year 2020 by applying estimates of percentage changes in food supply and serve as a reference for the reductions in the food consumption scenarios (OECD, FAO, 2012) (Table 5-1).

Table 5-1: Food supply in the reference scenario and changes in the food consumption scenarios

		Food consumption scenarios	
Food products	**Reference**	**Beef-dairy**	**Pig-poultry**
	kg/capita*year	%	%
Beef	12	-50	0
Dairy products	257	-50	0
Pork	54	0	-50
Poultry	16	0	-50
Eggs	12	0	-50
Other food	221	0	0
Cereals	141	17	13
Fruits and vegetables	213	17	13
Potatoes and starchy roots	70	17	13
Pulses	1	17	13

Own calculation based on FAO (2012); OECD and FAO (2012)

The food balance sheets data represent food supply, i.e. food intake plus food waste. For environmental impact assessment, supply data are relevant and not intake data, because environmental impacts are related to the food produced and not to the food consumed. The food consumption scenarios were designed in a way that reduces environmental impacts while ensuring healthy diets. A switch from current diets to healthy eating guidelines mainly results in a lower consumption of meat, dairy products, sugar and saturated fats and an increased consumption of fruits, vegetables, cereals, potatoes, tree nuts and vegetable fats (Arnoult et al., 2010; Audsley et al., 2010; Srinivasan et al., 2006; Tukker et al., 2011; Wirsenius et al., 2010a). Marlow et al. (2009) showed that vegetarian diets contain significantly more fruits, nuts and beans than non-vegetarian diets. The East Mediterranean diet as of the 1960s was rich in plant protein and low in meat protein and is considered both environmentally sustainable and healthy (Boer et al., 2006). Although the meat consumption in our food consumption scenarios is still slightly higher than recommended in McMichael et al. (2007), overall, our food consumption scenarios align better with healthy eating recommendations than initially.

5.2.3 Livestock production scenarios

The livestock production scenarios were implemented in the MITERRA model according to the food consumption scenarios, i.e., in the beef-dairy reduction scenario, the numbers of beef cattle and dairy cows were reduced by 50%, and in the pig-poultry reductions scenario, the numbers of pigs, poultry and laying hens were reduced by 50%. The feed use in the reference scenario was reduced in proportion to the reductions in the livestock production scenarios and was adjusted based on energy and protein content to not affect the animals’ nutritional requirements. The main feed components fodder, forage, protein-rich feed and energy-rich feed were reduced by 50% according to the reduction in livestock numbers to not affect animals’ diets (Table 5-2). The 50% reduction in the use of forage was achieved with proportionally higher reductions in fodder on arable land and lower reductions in grass from permanent grassland. Natural grassland was not reduced. The reasoning behind this scenario design was to assure that land freed up from fodder and forage production would be suitable for arable production (see land use scenarios, chapter 5.2.4). Imports of protein-rich and energy-rich feed were reduced, whereas domestic product use remained constant. In the final step, the feed cereals were reduced to balance livestock’s energy requirements.

Table 5-2: Use of main feed items in the reference and percentage reductions of feed use in the livestock production scenarios

Feed category	Feed sub-category	Reference	Livestock scenarios	
			Beef-dairy	Pig-poultry
		10^6 ton dm	%	%
Fodder	Fodder maize, fodder roots	26.5	50	0
Forage			50	0
	Fodder on arable land (incl. temporary grassland)	2.0	86	0
	Grass from permanent grassland	24.0	46	0
Protein-rich feed			50	50
	Domestic (oil seed cakes)	7.0	0	0
	Imports (soy-based)	5.1	52	31
Energy-rich feed			50	50
	Domestic (molasses)	0.3	0	0
	Imports (molasses, corn gluten feed, cassava)	0.7	19	48
Cereals		23	7	46

dm: dry matter
Feed use data in the reference taken from MITERRA

5.2.4 Land use scenarios

It was assumed that the increase in plant-based food consumption in the food consumption scenarios would translate into the proportional increase in plant-based food production. Further, it was assumed that the reduction in fodder and feed use in the livestock scenarios would translate into a proportional reduction in feed and fodder production. The increase in area used for additional plant-based food production and the decrease in area used for feed and fodder scenarios were implemented into the MITERRA model. On the net freed-up area, three scenarios for the alternative use of freed-up land were developed and analysed. These land use scenarios illustrate the key opportunities that arise from a reduction in livestock product consumption and production and reflect the key demand on agriculture: Food production, non-food biomass production and nature conservation.

Food supply: The agricultural sector maximises cereal production and export to increase global food supply and contribute to food security, e.g., demanded in the United Nations Sustainable Development Goals, for a growing population. Arable land previously used for feed, fodder or forage production and permanent grassland suitable for arable production was cultivated with cereals. The available area was corrected for the increase in seeds needed for additional production. Surplus cereals were exported.

Biomass: The agricultural sector strengthens lignocellulosic biomass production for energy use to contribute to the EU 20-20-20 policy targets or for material use to contribute to a bio-based economy. Arable land previously used for feed, fodder or forage production and permanent grassland suitable for arable production were cultivated with perennial lignocellulosic crops like canary reed, switchgrass, miscanthus, poplar or willow (Elbersen et al. 2013).

Biodiversity: The agricultural sector aims to halt the loss of terrestrial biodiversity and contribute to the "Greening" of the CAP reform 2014-2020 and to biodiversity conservation policies (European Communities, 2006). Arable land was turned into long-term agricultural fallows. Permanent grassland was maintained and managed extensively with lower nitrogen fertilisation and lower yields (Koellner and Scholz, 2007, 2008).

In the MITERRA model, permanent grassland area is categorised into intensive and extensive grassland and rough grazing area. In the food supply and biomass land use scenarios, we assumed that mainly intensive grassland was freed up to ensure that the land is suitable for arable production. In the biodiversity scenario, the reduction in forage demand resulted in lower grassland yields while maintaining all permanent grassland area. Thus, intensively managed grassland became extensively managed or semi-natural grassland.

5.2.5 Analysing environmental impacts

Scenario impacts on agricultural production and land use in Germany were analysed with the MITERRA model. Building on these results, biodiversity impacts of land use change were estimated based on the Environmental Damage Potential, a characterisation factor for different land use types (Koellner and Scholz, 2007, 2008). The Environmental Damage Potential refers to the number of vascular plants on a certain land use type and expresses the relative potential damage to species diversity of a certain land use type compared to regional average species richness. Land use types with fewer species numbers than the reference are considered detrimental and such with higher species number, beneficial. Impacts of land use change comprise impacts of land transformation, land occupation and land restoration and depend on the Environmental Damage Potential, the size of the area affected and the duration of impacts. We applied the transformation periods for changes in land use intensity as suggested in Koellner and Scholz (2007) and assumed duration of occupation of 20 years.

The MITERRA model estimated emissions of air pollutants (NH_3, primary fine particulate matter ($PM_{2.5}$)) and greenhouse gases (methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2)). Country-specific NH_3 emission factors were adapted from the GAINS model. To calculate emissions of $PM_{2.5}$, the $PM_{2.5}$ emission factors for different livestock types, arable land and agricultural fuel use were newly implemented into MITERRA for this study (European Environment Agency, 2013; Haenel, 2012). Greenhouse gas emission factors and soil carbon factors were based on IPCC (2006) (Lesschen et al., 2011). Changes in soil carbon stocks caused by changes in cropping shares were divided by 20 years to obtain annual CO_2 emissions. All greenhouse gas emissions were expressed in CO_2 equivalents (CO_2e) based on of the potential 100-year global warming values relative to carbon dioxide (CO_2: 1, CH_4: 25 and N_2O: 298) (IPCC, 2008). Mineral fertiliser use affecting N emissions was estimated in a balanced fertilisation approach that adjusted fertiliser application rates to crop requirements (Velthof et al., 2009). This approach was considered appropriate in order to balance the reduction of N input from livestock manure by a possible increase in mineral fertiliser and served as a benchmark to estimate impacts on nitrogen-related emissions.

The impacts of air pollution on human health were estimated with the concept of Disability Adjusted Life Years (DALY) that measures the amount of ill health caused by disability or premature death based on estimates derived with the EcoSense model. The impacts of NH_3 emissions and subsequent N deposition were visualised with critical load maps that estimated the exceedance of critical loads in natural ecosystems.

5.2.6 Estimating economic impacts

The external costs associated with the impacts of land use change on terrestrial biodiversity were estimated with restoration costs provided in Ott et al. (2006). The external costs of impacts on human health caused by NH_3 and $PM_{2.5}$ emissions and of impacts on terrestrial biodiversity caused by NH_3 emissions were derived from the EcoSense model. The external costs of greenhouse gas emissions were based on Umweltbundesamt (2007) (Wagner et al., 2015). The economic impacts on the agricultural sector were estimated based on production changes as a result of the scenarios and gross margins for the specific products (Hölscher et al., 2007; LWF; Sauer and Hardeweg, 2016). The economic impacts on private households were estimated from household expenditure data (Destatis, 2015).

5.3 Results and discussion

5.3.1 Scenario impacts on land use

A 50% reduction in livestock product consumption and production released up to 33% of the permanent grassland area and 23% of the cropland area, due to the reduced need for livestock fodder and feed production, totalling 24% of agricultural land in Germany (Table 5-3). The area freed up from fodder and feed production was about 9 times higher than the increase in area needed for domestic food production. As Germany is an importer of fruits and vegetables, the increase in imports would require about 0.6 million ha of land outside Germany. Still the diet shift resulted in a net release of agricultural land. Additionally, the reduction in feed imports of soy bean meal would free up about 2.4 million ha of land outside Germany, mainly in South America (based on FAOSTAT crop production data).

Other diet studies yielded results comparable to ours. (Gerbens-Leenes and Nonhebel, 2002) and (Peters et al., 2007) found that plant-based diets need about 5 to 6 times less land than diets rich in livestock products. Wirsenius et al. (2010a) showed that freed up land area due to lower meat consumption was about 10 times higher than the increase in land area due to higher consumption of vegetables and fruits. These studies support our results and affirm that a shift in diets towards less livestock production and consumption frees up land from feed production that can be used for alternative purposes.

Fodder and grassland area were freed up only in the beef -dairy reduction scenario, because pig and poultry are not fed on fodder and grass. The converted grassland area includes the total intensively managed grassland area and about 5% of the extensively managed grassland area. We consider this area suitable for crop production in the food supply and biomass land use scenarios.

A reduction in beef and dairy production freed up more agricultural land than a reduction in pig and poultry production, because the feed efficiency of beef and dairy production is lower than that of pigs and poultry. Yet a reduction in pig and poultry production freed up more cropland than a reduction in beef and dairy production, because monogastrics are mainly fed on cereals. Beef cattle and dairy cows need less cropland and are more efficient in food supply per unit of human-edible feed consumed than monogastrics and contribute thereby to food supply (Gill et al., 2010; Peters et al., 2007). From a food supply perspective, a certain level of cattle and dairy production is recommended to be maintained.

In our study we assumed that diet shifts would lead to proportional changes in agricultural production in Germany and neglected their impacts on markets and feedback on production. As can be seen in Tukker et al. (2011), when including market feedback, the relationship between consumption and production is non-linear. Domestic production changes to a lesser extent than consumption, and exports increase, while imports decrease. Thus, the potential of reducing environmental impacts in Germany will be less than indicated in Table 5-3. Hence, this study may overestimate the reduction in environmental impacts in Germany. Further, it neglects the effects elsewhere.

Table 5-3: Areas of grassland and crop land in the reference and changes in land use for the different land use and livestock scenarios in Germany in 2020 (in million hectares)

	Land use scenario	**Food supply**		**Biomass supply**		**Biodiversity**	
	Livestock scenario	**Beef-dairy**	**Pig-poultry**	**Beef-dairy**	**Pig-poultry**	**Beef-dairy**	**Pig-poultry**
Area (10^6 ha)	Reference						
Grassland	4.8	-1.6		-1.6			
Fodder	1.7	-1.0		-1.0		-1.0	
Feed cereals	3.7	-0.3	-1.7	-0.3	-1.7	-0.3	-1.7
Food area	2.7	+0.3	+0.2	+0.3	+0.2	+0.3	+0.2
Export cereals	0.9	+2.6	+1.5				
Lignocellulosic crops	0.001			+2.6	+1.5		
Fallows	0.9					+1.0	+1.5

Own calculation with MITERRA

In the food supply scenario, 22 million tonnes of cereals were exported additionally. Assuming a human energy consumption of 3000 kilocalories per day (Nelleman et al., 2009) and correcting for the land needed outside Germany for vegetable and fruit imports, about 55 million people could be fed additionally, representing about 6% of undernourished people in the world. These results are indeed indicative, because, on the one hand, people would not eat only cereals, and, on the other hand, cereals would make up about 75% in the crop rotation in Germany. Nevertheless they illustrate that a decrease in animal source food consumption in Germany can contribute to increased global food supply.

In the biomass scenario, the cultivation of lignocellulosic crops on 4.1 million ha yielded 36.5 million tons of biomass (dry matter), thereof 12.6 million tons of wood from short rotation coppice and 23.9 million tons of grassy biomass from switchgrass and miscanthus. If used for energy production, the lignocellulosic biomass would generate 550 petajoule of final heat energy and meet about 6% of final energy consumption or 14% of final heat energy consumption in 2020, contributing about 37% to Germany's renewable energy target (European Commission, 2010). To minimize the competition between food and energy production on cropland, the energy carrier per hectare of land needs to be as efficient as possible. Dupraz et al. (2011) showed that an agrivoltaic system, i.e., a combination of crop production and solar panels on the same land area, increases the overall productivity of the land by 60 to 70%. Dijkman and Benders (2010) found a higher ratio of energy density for wind and solar than for energy crops, with wind having the highest energy output/input ratio. Wind towers provide about 10 times more energy than perennial energy crops per unit of surface area. They also allow agricultural production, because they occupy only a small fraction of the land, and, like solar panels, could be placed on marginal land, reducing the competition with food production. The comparison of these values indicates that electricity from wind or solar on agricultural land is more efficient than heat produced from perennial energy crops. However, these energy carriers differ in application, seasonal variation and storage potentials. Alternatively, the lignocellulosic biomass could be used to produce sugars, e.g., for bulk chemicals and bioplastics, or wood composites. The potential yield of about 25 million tons of sugars would exceed the quantity of sugars used in industry in recent years (Raschka and Carus, 2012). The cultivation of 1.3 million ha of short rotation coppice would close the gap between wood demand and forestry wood supply in the year 2020, as expected by Thrän et al. (2011). Hence, land freed up from livestock production due to diet shifts can contribute to renewable energy supply or increase the potential to grow lignocellulosic biomass for material use.

In the biodiversity land use scenario, the extensification of permanent grassland led to 67% lower yields of intensive grassland and to 34% lower yields of extensive grassland, compared to the reference. In total, 1.2 million ha of formerly intensively managed grassland were then managed extensively, and 3.6 million ha of extensively managed grassland were turned into semi-natural grassland, which is valuable for biodiversity. In addition, 2.5 million ha of arable land were turned into fallows representing 30% of arable land. This share exceeds e.g. the goal of 7% of cropland as foreseen in the CAP reform 2014-2020. Thus, a diet shift provides scope for nature and biodiversity conservation.

5.3.2 Scenario impacts on atmospheric emissions and on soil carbon sequestration

A reduction in beef and dairy production and consumption achieved higher NH_3 emission reductions than in pig and poultry (Table 5-4). The variations were larger between the livestock scenarios than among the land use scenarios. The impact of alternative land use on NH_3 emissions is small, because 86% of NH_3 emissions originated from livestock. Assuming no changes in emissions from other economic sectors, total national emissions could be reduced by at least 16% in the pig and poultry reduction scenario and up to 27% in the beef and dairy reduction scenario, or, in the combination, by a maximum of 45%, equalling 193 Gg NH_3. A diet shift would easily achieve the reduction target of 29 Gg NH_3 of the Gothenburg Protocol (UNECE, 2013). This result indicates that policy targets could even be more ambitious. Tukker et al. (2011) showed that diets with low meat consumption reduced NH_3-related impacts of acidification and eutrophication. The NH_3 emission reduction of the diet shift we had analysed was higher than technical reduction potentials, which range from 23% to 38% (Oenema et al., 2007; Oenema et al., 2009; Wagner et al., 2012; Wagner et al., 2015). Hence, a reduction in livestock product consumption is an effective means for NH_3 emission reduction. The NH_3 emission reduction potentials are higher for the beef and dairy production and consumption scenario than for the pigs and poultry scenario. As the reduction potential associated with a 50% decrease of animal source food in the diet is higher than the technical reduction potential, it can be concluded that diet shifts should not be neglected as a complementary means to technical measures for NH_3 emission reduction.

Table 5-4: Emissions and soil carbon sequestration in the reference scenario (in Gg), and changes in emissions and soil carbon sequestration in the land use and livestock scenarios (in %) in Germany in 2020

	Land use scenario	**Food supply**		**Biomass**		**Biodiversity**	
	Livestock scenario	**Beef-dairy**	**Pig-poultry**	**Beef-dairy**	**Pig-poultry**	**Beef-dairy**	**Pig-poultry**
	Reference Gg	%					
NH_3	428	-23	-16	-26	-17	-27	-18
$PM_{2.5}$	6.8	-10	-15	-17	-18	-19	-19
GHG* (in CO_2e)	54,824	-26	-8	-30	-10	-30	-10
SOC (in C)	1,018,770	-5	0	3	4	1	2

*GHG = greenhouse gas
Own calculation with MITERRA

About 86% of $PM_{2.5}$ emissions in agriculture originated from livestock in the reference scenario. The reductions in the food supply scenario were lower than in the biomass and the biodiversity scenarios, because cereals produced on freed-up land emitted $PM_{2.5}$, whereas perennial lignocellulosic crops or grasslands and fallows did not emit $PM_{2.5}$. In the food supply scenario, the decrease in $PM_{2.5}$ emissions from livestock was partly offset by an increase in $PM_{2.5}$ emissions from arable land caused by the conversion of grassland into arable land. $PM_{2.5}$ emission from fuel use increased in the food supply scenario and in the biomass scenario due to the conversion of grassland into arable land and decreased in the biodiversity scenario because of the increase in fallow land. $PM_{2.5}$ emissions from fertiliser production slightly increased in the food supply scenario, but decreased in the biomass scenario and the biodiversity scenario, because less fertiliser was applied to perennial lignocellulosic crops and no fertiliser to fallows. The $PM_{2.5}$ emissions differ from those estimated in (Haenel, 2012), because they represent a scenario for 2020 and cover, besides livestock production and arable land, also $PM_{2.5}$ emissions from fuel use and from fertiliser production. The agricultural sector reduced total national emissions by about 2% and could contribute about 7% to the $PM_{2.5}$ emission reduction target of the Gothenburg Protocol of 31 Gg (UNECE, 2013). Like NH_3, the $PM_{2.5}$ emission reduction potential of this diet shift can be higher than the reduction potential of technical measures, which ranged from 5% for exhaust air purification in livestock production to up to 30% for conservation tillage in crop production, as estimated in Wagner et al. (2015). Our results indicate two aspects: A diet shift can be complementary to technical $PM_{2.5}$ emission reduction measures. However, livestock production is not an important sector for primary $PM_{2.5}$ emission reduction and related policies.

More greenhouse gas emissions were reduced in the beef and dairy reduction scenario than in the pig and poultry reduction scenario. The livestock types had a larger impact on greenhouse gas emission reductions than the land use types. In total, up to 40% of agricultural greenhouse gas emissions were reduced, contributing 22 Tg of CO_2e to greenhouse gas emission reduction targets. Assuming no changes in emissions from other sectors, the reduction would equal about 2% of national greenhouse gas emissions. In the biomass scenario, greenhouse gas emissions in the range of 40 Tg could be reduced additionally by replacing fossil fuels with bioenergy (Umweltbundesamt, 2014). However, a reduction in livestock production provides less manure for energy production in biogas plants and thus reduces the greenhouse gas reduction potential from biogas production. Other studies also found reductions in greenhouse gas emissions if livestock product consumption was reduced and diets shifted from livestock to plant-based food consumption (Audsley et al., 2010; Stehfest et al., 2009; Popp et al., 2010). Popp et al. (2010) showed additionally that diet shifts were more effective than technical measures and that highest reductions were achieved when both approaches were combined, what is also suggested by McMichael et al. (2007), Friel et al. (2009) and Garnett (2009). Bellarby et al. (2013) estimated a reduction potential of 15% to 30% for a combination of technical approaches. Hence, a reduction in livestock product consumption, particularly in beef and dairy products, is an effective means for greenhouse gas reduction in agriculture and can have a higher reduction potential than technical mitigation options.

The changes in soil carbon stocks and associated CO_2 emissions depended on grassland conversion and the new type of land use – up to 9 Tg CO_2e were released of the soil (food supply scenario), or, on the contrary, up to 11 Tg of CO_2e were reduced by soil carbon sequestration (biomass scenario). Soil carbon was released in the food supply scenario of the beef and dairy reduction scenario by converting grassland into arable land, whereas it was sequestered in the biomass and the biodiversity scenarios, because neither perennial lignocellulosic crops nor grassland or fallows were ploughed. The amount of sequestered carbon was higher in the pig and poultry reduction scenarios compared to the beef and dairy reduction scenarios, because grassland was maintained. Grassland plays an important role in soil carbon sequestration. Allard et al. (2007) and Bellarby et al. (2013) indicate that extensive beef and dairy production on grassland can be associated with a reduction in greenhouse gas emissions from cattle rearing. In the biomass scenarios, the sequestration was higher than in the biodiversity scenarios, because lignocellulosic biomass crops sequestered more soil carbon than agricultural fallows. In the biomass scenario with the highest cumulative reductions, soil carbon sequestration in agriculture equalled 52% of the direct greenhouse gas emission reduction and contributed 34% to the total cumulative greenhouse gas reduction. Thus, including soil carbon sequestration in greenhouse gas reduction strategies in agriculture contributes to achieving the greenhouse gas reduction targets. It should be noted, however, that, unlike reductions in methane or nitrous oxide emissions, carbon sequestration is a transient phenomenon, because carbon can be released from the soil again depending on the method and type of cultivation. Maintaining grassland and cultivating arable land with perennial lignocellulosic crops or turning them into fallows needs to be enhanced, whereas grassland conversion needs to be restricted.

5.3.3 Scenario impacts on biodiversity and human health

Land use change affected biodiversity. Biodiversity indicated by the Environmental Damage Potential increased in the biodiversity scenario, as intended, but decreased in the biomass and even more in the food supply scenario (Table 5-5). In the food supply scenario, grassland conversion to arable land was detrimental to biodiversity. These decreases resulted from a reduction in beef and dairy production. In the biomass scenario, the conversion of grasslands to lignocellulosic crop area was detrimental to biodiversity, whereas perennial lignocellulosic crop cultivation on former fodder area decreased the damages and thus was beneficial for biodiversity. Unlike expected, the change from intensively managed to extensively managed grassland in the biodiversity scenario increased the damages, while turning extensively managed into semi-natural grassland and fodder area into fallows decreased the damages and outweighed the effect of intensive grassland change. The benefits for biodiversity could be increased if grasslands were managed intensively or turned semi-natural.

Table 5-5: Damages of land use on biodiversity in the reference and changes in the land use scenarios (in %) in Germany in 2020

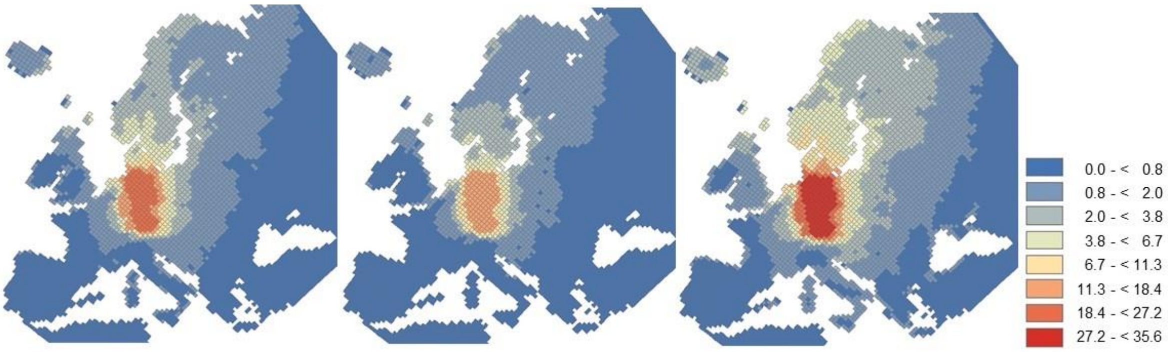
		Land use scenarios		
Scenario	**Reference**	**Food supply**	**Biomass**	**Biodiversity**
Unit	10^6 ha*a		%	
Grassland intensive	7.9	112	95	71
Grassland extensive	37.4	4	3	-236
Fodder and feed area	25.2	0	-12	-258
Total damage change		14	8	-209

Negative values express an increase in biodiversity
Own calculations based on EDP (Koellner and Scholz, 2007, 2008)

The Environmental Damage Potential factor applied to fallows includes hedgerows, which are not common in Germany. Thus, the benefits of turning fodder and feed area into fallows in the biodiversity scenario may be overestimated. To reach these benefits, planting hedgerows would need to be stimulated. The Environmental Damage Potential factors applied refer to Germany and Switzerland, and the reference refers to the Swiss Lowlands. This approach is considered appropriate in the European part of the diversity zones that include Germany (Koellner and Scholz, 2008). Our assumptions for transformation time of land use intensities are based on Koellner and Scholz (2007). The assumption for occupation time, however, is arbitrary. We reasoned that land use change would not be a short-term effect and chose the same period of 20 years as for greenhouse gas reductions by soil carbon sequestration. The period of occupation clearly influences the damages. Whether land use change, induced by a diet shift, contributes to the goal of halting the loss of biodiversity depends on the new land use on grassland and on feed and fodder area. Biodiversity can be increased by turning grasslands semi-natural and by cultivating arable land with perennial lignocellulosic crops or even more by turning them into fallows.

The reduction in soy bean imports may prevent deforestation, an indirect land use change effect of soy bean production, in Brazil, a main producer of soy beans. This would have additional beneficial impacts on biodiversity, because of the high quality of biodiversity and the long restoration time of rain forests (Baan et al., 2013; Barthlott et al., 2005).

The reduction in NH_3 emissions in the livestock and land use scenarios resulted in reductions in N deposition, not only in Germany but also beyond the German territory (Figure 5-2). Like reductions in NH_3 emissions, the decrease in N deposition was higher in the beef-dairy scenario than in the pig-poultry scenario.

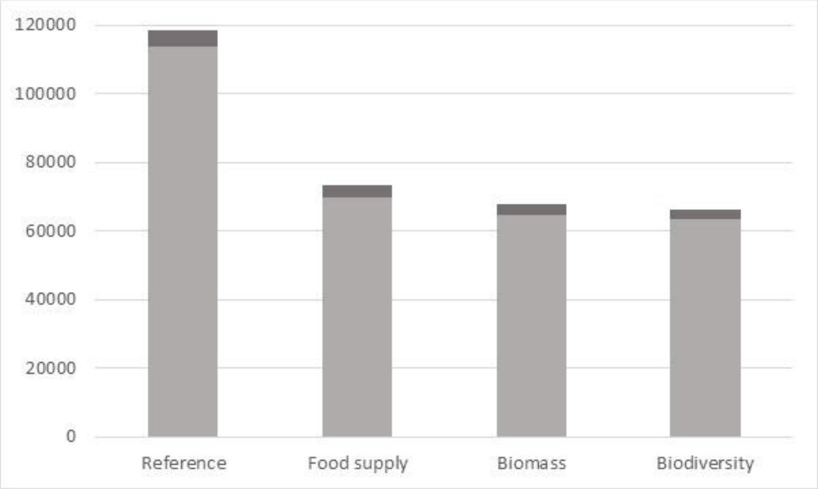


Left beef-dairy scenario, centre pig-poultry scenario, right all livestock reduction scenario

Figure 5-2: Reduction in N deposition (in %) in the biomass scenario compared to the reference

The reduction in N deposition would also reduce the exceedance of critical loads, an indicator for the level of atmospheric deposition below which no effects on natural ecosystems occur. Less exceedance of critical loads would result in a lower level of eutrophication and acidification of natural ecosystems and would reduce the loss of biodiversity.

The reductions in NH_3 emissions as well as in $PM_{2.5}$ emissions also reduced adverse impacts on human health (Figure 5-3). The disability-adjusted life years were reduced from about 119,000 years in the reference to about 66,000 years in the biodiversity scenario. About 95% of disability-adjusted life years were caused by NH_3 emissions.



Own calculations based on EcoSense

Figure 5-3: Disability-adjusted life years caused by NH_3 and $PM_{2.5}$ emissions in the land use scenarios (in years)

5.3.4 Scenario impacts on economic aspects

The total external costs of environmental impacts increased in the food supply scenario compared to the reference, decreased in the biomass scenario and were negative in the biodiversity scenario, i.e., the biodiversity scenario achieved positive external effects (Table 5-6). The changes in external costs of biodiversity impacts of land use change were crucial and had the strongest impact on total external cost estimates. The increase in external costs in the food supply scenario needs to be traded off for to the fact that this scenario provides food for 50 million people in addition.

Table 5-6: External costs of environmental impacts (in million EUR)

		Land use scenarios		
	Reference	**Food supply**	**Biomass**	**Biodiversity**
Biodiversity (land use)	0	9,205	3,867	-47,189
Biodiversity (NH_3)	4,808	2,945	2,729	2,673
Health	6,947	4,325	3,984	3,896
Climate change	4,422	3,633	1,815	2,270
Total	16,177	20,108	12,395	-38,350

Own calculations based on EcoSense (Ott et al., 2006; Umweltbundesamt, 2007)

The agricultural sector income decreased in all land use scenarios compared to the reference and the most in the biodiversity scenario with a reduction of 9% (Table 5-7). According to the scenario design, livestock producers incurred high income losses, whereas arable farms increased their income, particularly in the food supply scenario. The implementation of these scenarios would result in structural changes in the German agricultural sector. The increase in crop production including lignocellulosic crops would offer income opportunities for arable farms, whereas the reduction in livestock production would lead to considerable income losses for livestock producers, particularly in grassland areas.

Table 5-7: Agricultural sector income in the reference and the land use scenarios (in million EUR) and relative changes (in %) in the land use scenarios compared to the reference

		Land use scenarios		
	Reference	**Food supply**	**Biomass**	**Biodiversity**
Beef and dairy	9,636	4,818	4,818	4,818
Pigs and poultry	1,670	835	835	835
Cereals	5,181	7,075	3,974	3,974
Fruits, vegetables and pulses	16,007	19,083	19,083	19,083
Lignocellulosic biomass	4	0	1,707	0
Fallows	227	227	227	888
Total	32,726	32,038	30,643	29,597
Relative change		-2	-7	-9

Own calculations based on Sauer and Hardeweg (2016)

A diet shift from animal-based food to plant-based food according to the food consumption scenario reduced household expenditure for food by about 180 EUR (5%) per household and year totalling about 8,300 million EUR (own calculations based on Destatis, 2015). Tukker et al. (2011) showed that the environmental impacts of spending this extra purchasing power on non-food products are negligible.

The comparison of these economic impacts shows that the reduction of external costs in the biomass and the biodiversity scenario were higher than the income loss of the agricultural sector. Furthermore, the savings in private household expenditures on food was higher than the agricultural income loss in all scenarios.

5.3.5 Stimulating changes in food consumption patterns

This study showed that changes in food consumption patterns from livestock to plant-based food have manifold positive impacts on the environment and possibly also on human health. We arbitrarily assumed that these changes happen spontaneously. However, these changes need to be stimulated, e.g. by setting incentives via fiscal policy. Food taxes may alter food consumption in the expected direction (Thow et al., 2010). Wirsenius et al. (2010b) considered taxes on animal products as an effective means to reduce greenhouse gas emissions. Similarly, Edjabou and Smed (2013) regarded consumption taxes as a low cost option to promote climate friendly diets. Yet Waterlander et al. (2013) showed that promoting vegetables and fruits by discounting was more effective than food taxes on undesired food, particularly in combination with nutritional education. These studies show that various options to incentivise diet shifts exist.

5.4 Conclusions

A 50% decrease in animal-based food in Germany not only aligned better with healthy eating guidelines but freed up 2.5 million ha of arable land and 1.6 million ha of grassland from livestock feed and fodder production. This land area could be used to contribute to societal goals such as increasing food supply, biomass supply for energy or material use or nature conservation areas. Cultivating cereals could nourish 55 million people additionally and contribute to food supply and increase food security, but adversely affects biodiversity because of grassland conversion and non-divers crop rotations. Our results indicate that wind and solar would be more efficient per unit surface area than perennial lignocellulosic crops or other types of biomass. Therefore, it can be suggested that renewable energy is produced by wind or solar, and the remaining area could be used for other purposes such as material use. Considering biodiversity preservation, grassland conversion was detrimental to the natural environment, whereas perennial energy crop cultivation on former fodder and feed area, grassland extensification and fallows were beneficial. The diet shift reduced NH_3 emissions from agriculture by up to 45% (193 Gg) and national emissions by 42%. This amount of NH_3 reduced exceeds the technical reduction potentials and the NH_3 abatement target agreed in the Gothenburg Protocol. Therefore, a diet shift should be considered to complement technical measures. $PM_{2.5}$ emissions were reduced by up to 38%, and greenhouse gas emissions, up to 40%, representing 2% of national emissions each. Thus, the contribution of such a diet shift to reductions in $PM_{2.5}$ emissions and greenhouse gases are small. Additional greenhouse gas emissions could be reduced by replacing fossil fuels with renewable energy. The amount of soil carbon sequestered depended on the type of land use on the freed up area. Grassland conversion released carbon, whereas perennial energy crop cultivation and fallows accumulated it. Soil carbon sequestration provided a higher greenhouse gas reduction potential than the livestock reduction directly.

External costs decreased in the biomass and the biodiversity scenarios but increased in the food supply scenario. However, it needs to be considered that in the food supply scenario 50 million people can be nourished additionally. The reductions in external costs and food expenditures of private households may justify the compensation of the income losses in the agricultural sector.

Drawing an overall conclusion, the freed up arable land can be used for food and lignocellulosic biomass production and can partly be set aside for biodiversity preservation. Grassland should be maintained for biodiversity preservation and soil carbon sequestration.

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6 General Discussion

6.1 Synthesis

This final chapter summarises and synthesises the main findings from the previous research chapters and answers and discusses the main research questions of this thesis. Finally, overall conclusions are drawn and suggestions for future research formulated.

6.1.1 Main findings

The cost-benefit analysis proved to be a feasible and appropriate tool for the assessment of NH_3 and PM emission abatement measures, particularly in the presence of interactions both among NH_3 and PM emission abatement and greenhouse gas emissions. The monetary valuation of physical impacts led to damage cost estimates.

The abatement potentials of the technical abatement measures and the diet shift are shown in Table 6-1. The technical abatement measures with the highest NH_3 emission reduction were the substitution of urea fertiliser in crop production, manure application with injection or cultivator and exhaust air purification with a 1-stage chemical washer in livestock production. Conservation tillage achieved the most reductions of PM_{10} and $PM_{2.5}$. High reductions were achieved by low-nitrogen feeding of poultry and by exhaust air purification techniques. The diet shift resulted in high reductions of both NH_3 emissions (39% to 45%) and $PM_{2.5}$ emissions (25% to 38%). Combinations of technical NH_3 emission abatement measures achieved about 30% reductions and thus less than the diet shift. The $PM_{2.5}$ abatement potential of combinations of technical measures was about 30% to 35% and thus similar to those of a diet shift. The diet shift in Germany resulted in NH_3 emission reductions that were similar to those of a diet shift in the EU (about 40%, see chapter 4).

The results of abated emissions in Table 6-1 confirm that interactions exist between NH_3 and PM emission abatement and greenhouse gas emissions. Moreover, in some cases, NH_3 and PM emission abatement interacted as well. All NH_3 and PM emission abatement measures affected greenhouse gas emissions. Urea substitution, low-protein feeding and exhaust air purification systems also interacted among NH_3 and PM emissions. Not only synergies but also trade-offs occurred. Low-nitrogen feeding of poultry, manure storage cover techniques and biofilters for reducing PM in exhaust air increased greenhouse gas emissions, while the latter also increased NH_3 emissions. In general, the greenhouse gas reductions of the technical NH_3 and PM emission abatement measures were small, except for the reduction achieved with conservation tillage via soil carbon sequestration in Baden-Württemberg. Reductions of greenhouse gas emissions were a side-effect of air pollutant abatement measures. The greenhouse gas reductions of a diet shift were large and exceeded those of the technical NH_3 and PM emission abatement measures, particularly with soil carbon sequestration in the biomass and biodiversity scenarios. In the food supply scenario, land use change released soil carbon. The reductions in Germany were in the same range as those in the EU (see chapter 4).

Table 6-1: Emissions of NH$_3$, PM$_{10}$, PM$_{2.5}$ and greenhouse gases for three Federal States in Germany and national totals (reference, in Gg) and emission abatement potentials of technical measures and diet shifts compared to the reference (in %)

	NH$_3$	PM$_{10}$	PM$_{2.5}$	GHG	GHG total*
Reference	Gg				
Baden-Württemberg (2015)	38.0	10.5	2.0	6,838	
Brandenburg (2015)	19.9	12.9	2.9	5,637	
Lower Saxony (2015)	104.7	31.1	4.7	15,220	
Germany (2020)	352.7	n.c.	6.8	54,824	
	Changes compared to the reference (%)				
Crop production					
Urea substitution					
Baden-Württemberg	-13.3	n/a	-0.1	-1.5	
Brandenburg	-27.2	n/a	-0.5	-2.9	
Reduced tillage					
Baden-Württemberg	n/a	-40.0	-30.0	-1.9	-17.8
Brandenburg	n/a	-43.4	-24.1	-0.5	-3.3
Livestock production *(Lower Saxony)*					
Low-protein feeding					
Pigs	-1.5	-0.3	-0.2	-6.3	
Poultry	-2.5	-12.5	-20.8	+4.2	
Manure storage cover					
Granulates	-5.8	n/a	n/a	+1.5	
Swimming foil	-5.3	n/a	n/a	+1.5	
Concrete cover	-8.6	n/a	n/a	+0.9	
Manure application		n/a	n/a		
Trailing hose	-2.0	n/a	n/a	-0.1	
Trailing shoe	-10.4	n/a	n/a	-0.6	
Injection / cultivator	-13.7	n/a	n/a	-2.4	
Exhaust air purification					
1-stage chemical washer	-13.3	-7.6	-4.9	-2.7	
3-stage system	-12.7	-7.6	-4.9	-0.4	
Biofilter	+1.2	-7.6	-4.9	+0.2	
Diet shift *(Germany)*					
Food supply	-39	n.c.	-25	-34	-18
Biomass	-43	n.c.	-35	-40	-59
Biodiversity	-45	n.c.	-38	-40	-49

Technical abatement potentials from Beletskaya (2016); abatement potentials of a diet shift own calculations in this thesis

GHG: greenhouse gas emissions

*GHG total: including changes in CO$_2$ via soil carbon sequestration

n/a: not applicable; n.c.: not calculated

The cost estimates of the technical abatement measures (Table 6-2) show that the gross margins increased when implementing reduced tillage or low-nitrogen feeding of pigs. These measures were profitable for farmers. The implementation of all other measures decreased the gross margins and caused costs. The net benefits resulted from the benefits less the abatement costs. 1-stage exhaust air purification systems achieved the highest net benefits, while urea substitution achieved the highest benefit-to-cost ratio. Low-nitrogen poultry feeding, manure application with trailing hose and biofilter for exhaust air purification achieved negative net benefits and benefit-to-cost ratios below 1; i.e., their abatement costs exceeded the benefits and, thus, they were not cost-efficient. Hence, unlike I had expected, not all technical abatement measures yielded benefits that exceeded the abatement costs.

The loss in agricultural income in the diet shift scenario was small in the food supply scenario (2%) with additional cereal production, higher in the biomass scenario (7%) and highest in the biodiversity scenario (10%) due to the extensification of agricultural production (Table 6-2). All scenarios yielded positive net benefits and benefit-to-cost ratios larger than 1. The biomass scenario achieved the highest net benefits while the food supply scenario had the highest benefit-to-cost ratio.

Table 6-2: Costs, benefits and resulting net benefits (in million EUR) and benefit-to-cost ratios of technical abatement measures in three Federal States and of diet shifts in Germany

Measures	**Costs**	**Benefits**			**Net benefits**	**Benefit-to-cost ratio**
		NH_3	PM	GHG[*]		
Crop production						
Urea substitution						
Baden-Württemberg	15	114	0	7	106	8.1
Brandenburg	16	122	1	12	119	8.4
Reduced tillage						
Baden-Württemberg	-63[a]	n/a	49	85	197	High
Brandenburg	-28[a]	n/a	60	13	101	High
Livestock production *(Lower Saxony)*						
Low-protein feeding						
Pigs	-32[a]	36	1	70	138	High
Poultry	106	60	71	-46[b]	-21	0.8
Manure storage						
Granulates	16	137	0	-17[b]	105	7.6
Swimming foil	45	123	0	-17[b]	62	2.4
Concrete cover	37	203	0	-10[b]	156	5.2
Manure application						
Trailing hose	54	47	0	1	-6	0.9
Trailing shoe	80	247	0	7	174	3.2
Injection / cultivator	89	324	0	27	261	3.9
Exhaust air purification						
1-stage chemical washer	76	313	20	30	286	4.8
3-stage system	148	299	20	4	175	2.2
Biofilter	49	-27[b]	20	-2[b]	-59	Negative
Diet shift *(Germany)*						
Food supply	688	4,362	124	789	4,586	7.7
Biomass	2,083	4,867	175	2,607	5,565	3.7
Biodiversity	3,129	4,999	188	2,152	4,209	2.3

Technical abatement costs from Beletskaya (2016); costs of diet shift and all benefit estimates own calculations in this thesis

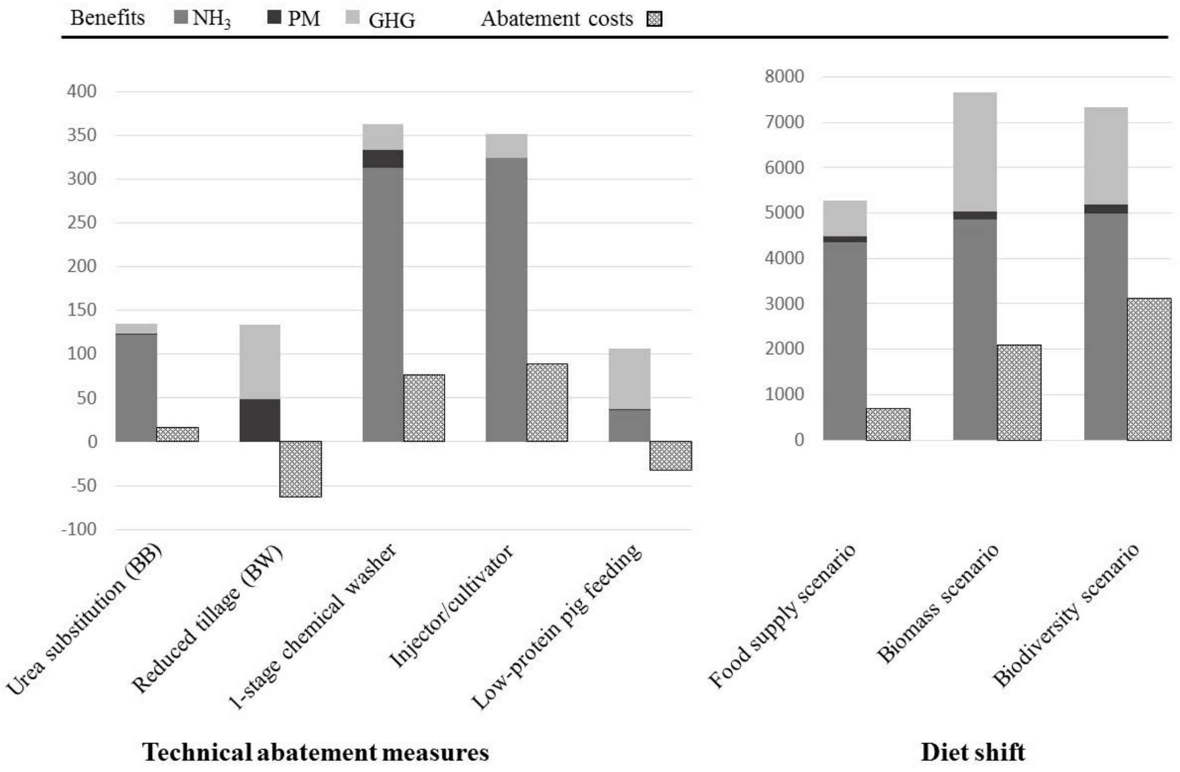
[*] GHG = greenhouse gas emissions

[a] the negative algebraic sign shows that the measure increased farm gross margins; thus was profitable per se

[b] the negative algebraic sign shows that the measure increased damage costs

n/a: not applicable

According to the emission reductions, the benefits consisted of benefits from reductions of all types of emissions. Measures that increased greenhouse gas emissions increased the damage costs of greenhouse gases (Table 6-2). This increase again resulted in a decrease in total benefits and net benefits and a lower benefit-to-cost ratio. Measures that reduced also greenhouse gases increased their benefits. Hence, synergies in interactions increased the benefits of the abatement measures and improved their cost-efficiency, whereas antagonistic interactions decreased the benefits and downgraded their cost-efficiency. The influence of interactions will be discussed in more detail in section 6.1.4.



BB: Brandenburg, BW: Baden-Württemberg; mind the different scales on the axes of ordinates

Figure 6-1: Comparison of abatement costs and benefits per emission type for a selection of technical emission abatement measures and for the land use scenarios of the diet shift based on Table 6-2 (in million EUR)

Figure 6-1 visualizes the total benefits disaggregated per emission type and the abatement costs for a selection of technical emission abatement measures and for the land use scenarios in the diet shift study based on Table 6-2. The negative abatement costs of reduced tillage and low-protein pig feeding represent the increase in farmers' gross margins. The benefits of NH_3 emission reduction contributed most to the total benefits for most of the abatement measures. However, the side-benefits of greenhouse gas emission reductions exceeded those of NH_3 or PM emission reduction for reduced tillage and low-protein pig feeding.

6.1.2 Cost-benefit-analysis

The assessments in this thesis were carried out in cost-benefit analyses by applying the impact-pathway approach combined with monetary valuation. The impact-pathway approach allows identifying and quantifying physical impacts such as cases of chronic bronchitis and biodiversity loss. However, these impacts lack a common indicator for comparison. Therefore, the impact-pathway approach was combined with the monetary valuation of impacts. A monetary valuation of the impacts of emission abatement can provide decision makers with useful information for balancing environmental ambition and economic implications. However, monetary valuation of impacts is not without debate, particularly when it comes to attribute economic values to non-market goods, most notably human life and ecosystems (e.g. Costanza, 2006).

Technical NH_3 emission abatement measures have been assessed in cost-effectiveness analyses (e.g. Döhler et al., 2011; Oenema et al., 2009; Wagner et al., 2012; Webb et al., 2006). This approach results in costs per quantity of NH_3 reduced and is straightforward if one pollutant is included. However, cost-effectiveness analyses have their limitations if the abatement measure affects more than one pollutant. The studies focussing only on NH_3 emissions neglect possible interrelations among NH_3 and other types of emissions. Oenema et al. (2009) analysed measures that reduce emissions of nitrogen (NH_3, N_2O, NO_3, NO_x). These measures could be assessed according to their cost-effectiveness by linking them to nitrogen as common unit. Yet these emissions have different impacts and therefore cannot be compared and combined. Brink et al. (2005) included emissions of NH_3, N_2O and CH_4 in the analysis and aggregated N_2O and CH_4 into CO_2-equivalents. The studies carried out with the GAINS model, e.g. Amann et al. (2011), focus on air pollutant abatement measures and their interactions with greenhouse gases. They include greenhouse gas emission rates and the associated value per ton of CO_2-equivalents. Thus, greenhouse gases were comprised like in Brink et al. (2005) and, additionally, the effects of greenhouse gases were monetised. A further step towards monetisation was taken by Eory et al. (2013) when they combined a cost-effectiveness analysis with monetary values of side effects of emission reduction. They multiplied the quantitative emission reduction with the damage costs of the pollutants. This approach required external cost estimates and comes close to the cost-benefit analysis in our study.

The environmental impacts of food products and human diets have been assessed with different approaches. On a food product level, life cycle assessments have been carried out. They assess the environmental impacts and resources used throughout a product’s life from raw material acquisition through production use and disposal and result in the environmental impact per product. With such an approach, nitrogen and greenhouse gas emissions per food product were identified (e.g. Leip et al., 2014; Carlsson-Kanyama and González, 2009). A life cycle assessment does not include an economic assessment, but can for example be combined with an environmentally extended input-output analysis. Such an approach was applied in Tukker et al. (2011) for analysing environmental impacts of food consumption patterns. The input-output matrices describe trade between industries in monetary terms and can include environmental impacts by adding emissions coefficients. Tukker et al. (2011) included indicators for different environmental impacts such as climate change, terrestrial acidification and freshwater eutrophication.

Thus, one advantage of a cost-benefit analysis is that several emission types and different types of impacts can be assessed. The second advantage is internalising external costs. Estimating damage costs, as done by monetising physical impacts, is a precondition for internalising external costs of agricultural production. This approach enabled insight into the external effects of agricultural production. It made the different impacts, such as on human health, biodiversity and the climate, comparable and helped to understand what the different impacts add to external costs and what external costs can be avoided if emissions are reduced. The comparison of abatement costs and benefits indicate the welfare gains and opens scope for subsidising farmers to reduce emissions. Oenema et al. (2009), for example, point out that the income effects of N reduction are significant. If these losses were compared to the damage costs avoided, this would show how profitable emission abatement can be for the society.

Despite some controversies about the monetary valuation of physical impacts of emission abatement and uncertainties related to valuation studies (also addressed in chapter 2), the cost-benefit analysis in this thesis confirmed to be a useful approach for assessing abatement measures, particularly in a multi-pollutant multi-effect context.

6.1.3 Abatement potentials, costs and benefits

Abatement potentials

The emission abatement potentials of technical measures were estimated with the economic-ecological farm model EFEM (Beletskaya, 2016), while those of a diet shift were estimated with the model MITERRA, a biophysical model without economic aspects. The technical abatement potentials reflect farmers’ profit-maximising behaviour and their economic responses to the implementation of abatement measures that may lead to changes in farm management and production. The technical abatement potentials may be overestimated, because they reflect optimised solutions. Being a supply-side model, EFEM does not include demand for agricultural products and thus market effects of changes in production costs and prices and possible changes in demand that may also influence emission abatement potentials (see chapter 2). In the analysis of the diet shift it was assumed that agricultural and livestock production would change proportionally to changes in food consumption. This approach neglects the feedback of market effects of changes in food demand and equilibrium prices and farmers’ adaptation to those changes. Tukker et al. (2011) showed that, when including market effects, the domestic changes in agricultural production were smaller, and exports increased while imports decreased. This issue indicates that the abatement potentials of the diet shift in Germany may be overestimated. The effects depend on assumptions made on trade and trade policies (see chapter 4 and 5).

Differences in abatement potentials may also result from emission factors implemented and the depiction of production processes in the models. EFEM depicts production processes leading to NH_3 emissions at detailed level following Haenel (2010), while the NH_3 emission factors in MITERRA, based on the GAINS model, are more aggregated. The greenhouse gas emissions and the $PM_{2.5}$ emissions may be underestimated in MITERRA compared to EFEM, because they exclude emissions from purchased feed, and the $PM_{2.5}$ emission estimates also exclude those from fertiliser production. The potentials of sequestering soil carbon are different, because EFEM includes region-specific and soil-specific carbon sequestration factors, while MITERRA applies the IPCC default value.

Furthermore, the assessment of the technical abatement potentials and the diet shift refer to different years and spatial scales. This aspect leads to different reference situations concerning livestock numbers, arable production and related emissions as well as cost and benefit estimates. The assessment of technical abatement measures in EFEM focus on regions with specialised crop or livestock production that may overestimate abatement potentials, while the diet shift was analysed at national level resulting in a more general picture.

A more comprehensive assessment of a combination of diet shifts and technical measures, as for example done for greenhouse gases in Popp et al. (2010), would be useful. The interrelation of these measures may affect the abatement potentials and may lead to changes in cost-benefit ratios and the cost-efficiency. Such an analysis could be carried out by coupling EFEM or MITERRA with an agricultural partial equilibrium model that depicts market effects and feeds them back to the agricultural emission model. A partial equilibrium model was not accessible in this thesis research.

The NH_3 emission abatement potentials of technical measures in this thesis are in the range of other studies (Döhler et al., 2011; Oenema et al., 2009; Wagner et al., 2012). Bellarby et al. (2013) estimated a greenhouse gas reduction potential for a combination of technical approaches that is higher than the greenhouse gas reductions in this thesis; however, the reductions in greenhouse gas emissions in this thesis were a side-effect of NH_3 and PM emission abatement measures. Diet shifts also reduce greenhouse gas emissions (Audsley et al., 2010; Stehfest et al., 2009; Popp et al., 2010). Popp et al. (2010) showed additionally that diet shifts were more effective in greenhouse gas reduction than technical measures and that highest reductions were achieved when both approaches were combined. Stehfest et al. (2009) point out that carbon sequestration on land freed up from feed production has a high potential for greenhouse gas reductions. This issue supports my finding that land use activities that increase soil carbon sequestration can contribute considerable to greenhouse gas reductions.

Abatement costs

Like the technical abatement potentials, the technical abatement costs were estimated with the bioeconomic model EFEM. The technical abatement costs reflect farmers' economic adaptation to the implementation of abatement measures which may include changes in production quantities and structure. The abatement costs for farmers of a diet shift were estimated with standard gross margins based on literature reviews, because the model MITERRA does not cover economic aspects. Such a static approach neglects possible behavioural changes of farmers. Additionally, the different time references – year 2015 for technical measures and year 2020 for diet shifts – make the comparison more difficult, because producer and consumer prices may differ.

The average NH_3 emission abatement costs for technical measures range between the cost estimates in other studies (Wagner et al., 2012; Oenema et al., 2009; Döhler et al., 2011; Bittman et al., 2014). The abatement costs included the effects on farm income, but not on the upstream and processing industry and consumers, as done in Oenema et al. (2009). Including these aspects could increase the technical abatement costs in this thesis.

Farmers' abatement costs for a diet shift ranged from 3.4-11.2 EUR per kilogramme NH_3 reduced, 9.6-31.2 EUR per kilogramme $PM_{2.5}$ reduced and 0.01-0.03 EUR per kilogramme greenhouse gas emissions reduced (values derived from results in chapter 5). They were estimated with standard gross margins and other data from the literature similar to the approach of Henze et al. (1998) and do not reflect farm types nor farmers' economic responses to changes in food consumption and potential price changes. Arnoult et al. (2010) showed that the livestock sector loses income, especially remote pastoral regions not suited for crop production, because their alternatives to livestock production are limited. Specialised crop production areas and arable farms and fruit and vegetable growers would benefit from the diet shift. The increase in the value of crops for direct human consumption would not compensate the reduction in the farm gate value of livestock from dietary change, as shown in Audsley et al. (2010). The economic impact of a production change at farm level depends crucially on the replacement activity on the land freed-up from livestock production. A regional analysis with a farm model would identify the farm types and regions most affected. The cost estimates focus on the farmers' income and exclude effects on the upstream and food processing industry, as considered in Henze et al. (1998). The effects on consumer income are considered negligible, because the diet shift increased the purchase power by about 0.5%

(chapter 5). Exploring economic effects of a diet shift on producer and consumer welfare with economic models may be appropriate. However, the effects depend on the type of model (general equilibrium versus partial equilibrium models), on the alteration of demand functions and on the approach for modelling trade and trade policies (Stehfest et al., 2013).

Benefits of changes in externalities

The atmospheric dispersion modelling in EcoSense is based on linear source-receptor relations between changes in emissions and subsequent changes in air pollution concentrations that do not adequately represent the non-linear processes in the atmosphere, as argued in Brandt et al. (2013). The health impacts were derived by linking changes in pollutant concentration to exposed human population via linear concentration-response-functions, which are also applied in other studies (Holland et al., 2005; Brandt et al., 2013) and are associated with uncertainties (Moldanová et al., 2011). The biodiversity impacts of N deposition are based on an indicator for natural landscape conditions in the Netherlands. Both countries have a high share of pressure from N deposition and a high share of critical loads exceedance. Nevertheless, the transfer of this indicator is related to high uncertainties. The damage costs for health and biodiversity include non-market values that were derived from willingness-to-pay analyses. The values are based on comprehensive studies and compared to meta-studies and are considered reliable (Desaigues et al., 2007; Desaigues et al., 2011; Kuik et al., 2007). Based on the detailed analysis in chapter 2, the health benefit estimates can be considered conservative, whereas the benefit estimates for biodiversity impacts can be considered uncertain. The value for damage costs by greenhouse gas emissions was taken from Umweltbundesamt (2007) and is based on several studies that estimated damage costs of climate change.

Not all technical measures were cost-efficient, i.e. the abatement costs exceeded the benefits in some cases. These findings indicate that it is important to estimate not only costs but also benefits. In the light of the uncertainties related to the assessment and the limitations of the study, the net benefits and relatively high benefit-to-cost ratios of 1-stage chemical washers, manure storage cover with granulates or concrete, manure application with injection or cultivator, low-nitrogen pig feeding, urea substitution and reduced tillage, can be considered robust. These measures can be recommended for implementation.

To compare the impacts of a diet shift to technical emission reduction measures, the benefits of reductions in emissions of NH_3, $PM_{2.5}$ and greenhouse gases were used. A more comprehensive assessment of diet shifts showed that the benefits largely depend on the replacement product on land freed-up from livestock production and the impacts of land use change on biodiversity.

Including biodiversity impacts of land use change would reduce the benefits in the food supply scenario and increase the benefits in the biomass scenario and particularly in the biodiversity scenario. However, it would have to be considered that the food supply scenario would nourish about 55 million people in addition. Moreover, a diet shift towards healthy plant-based food products would directly benefit human health by reducing the consumption of red meat and saturated fat and associated risks of cardiovascular diseases and colorectal cancer, as argued in chapter 4. Including associated reductions in disability-adjusted life years would increase the benefits in all scenarios and would make diet shifts more profitable.

6.1.4 Synergies of NH_3 and PM emission abatement with greenhouse gases

This thesis confirmed that interactions among the abatement of NH_3 and PM emissions with greenhouse gas emissions exist, both for technical abatement measures as well as for a shift in diets. This aspect had already been addressed in other studies that are in accordance with my results (e.g. Amann et al., 2011; Brink et al., 2005; Oenema et al., 2009; Winiwarter and Klimont, 2011). These interactions influence the cost-efficiency of the measures compared to a single-pollutant approach (Table 6-2). The cost-efficiency of biofilters used for exhaust air purification of PM emissions decreased, because biofilters increased NH_3 emissions and greenhouse gas emissions and thus related damage costs.

Including greenhouse gas emissions in the assessment of NH_3 and PM emission abatement measures led to efficiency gains of a 100% net benefit increase for low-protein feeding of pigs, of 75% net benefit increase for reduced tillage in Baden-Württemberg and of 15% net benefit increase for reduced tillage in Brandenburg. 1-stage washers and manure injection increased their net benefits by about 10%. All manure application techniques, particularly slurry injection, achieved additional benefits from greenhouse gas emission reduction and increased their total benefits and thus their cost-efficiency.

The benefits of the diet shift mainly resulted from NH_3 emission reduction. Regarding lignocellulosic biomass production or biodiversity conservation, a high share of the benefits stemmed from greenhouse gas emission reductions and increased the benefits. Abatement of $PM_{2.5}$ emissions contributed only 2% to 3% to the total benefits. If the additional greenhouse gas emission reductions of replacing fossil fuels with energy from perennial energy crops were considered, the majority of benefits originated from greenhouse gas emission reductions.

In multi-pollutant analyses, the abatement costs can be given in an aggregated manner without deriving the average abatement costs per pollutant (e.g. Brink et al., 2005; Oenema et al., 2009) or can be related to the main pollutant, as is usually done in studies with the GAINS model. The reduction of other pollutants is then considered a side-effect free of costs. This approach includes the question, which pollutant is considered the main pollutant. For example, conservation tillage in Baden-Württemberg reduced relatively more PM emissions than greenhouse gases; the benefits of greenhouse gas emission reduction exceeded those of PM emission reduction. The situation is similar for low nitrogen pig feeding, where NH_3 was the main pollutant, but the side-benefits of greenhouse gas emission reduction exceeded those of NH_3 emission reduction. Thus, although NH_3 or PM emissions were the main pollutant, the main benefits resulted from greenhouse gas emission reduction. One may think about allocating the abatement costs to the different pollutants by weighing the costs according to the pollutant's percentage contribution to the total benefits. In this manner, e.g. the abatement costs for manure injection decrease by about 8% from 7.5 to 7.0 EUR per kg NH_3-N, and the remaining costs would be allocated to the reduction of greenhouse gases at 0.02 EUR per kg greenhouse gas emissions. For the 1-stage chemical washer, 86% of total costs would be allocated to NH_3 emission reduction, 5% to PM and 8% to greenhouse gas emission reduction. The costs of a diet shift were allocated to NH_3 emission reduction by 64% to 83% and to greenhouse gases by 15% to 34%. Thus, if co-benefits of measures can be identified, costs can be divided among environmental targets.

These findings imply for science that the reductions of air pollutants and greenhouse gases be analysed in integrated assessments. In the design of policies for emission reduction, these interactions should also be taken into account, and air quality and climate policies should be harmonised to avoid technologies that reduce air pollution but at the same time contribute to climate change, and vice versa.

6.1.5 Conclusions

This thesis assessed technical NH_3 and PM emission abatement measures in agriculture and a shift in diets including interactions with greenhouse gas emissions in a cost-benefit analysis. The approach combined agricultural emissions modelling with impact assessment modelling applying the impact-pathway approach in combination with monetary impact valuation.

The results show that essentially all NH_3 and PM emission abatement measures affect also greenhouse gas emissions, either beneficially or adversely. Most of the measures are cost-efficient; i.e. the benefits achieved exceed the abatement costs. Those measures that were not cost-efficient such as low-protein poultry feeding and manure application with trailing hose in Lower Saxony should not be implemented. Beneficial interactions of NH_3 and PM emission abatement measures with greenhouse gas emissions increase the cost-efficiency of the measures, whereas adverse interactions decrease it. For reduced tillage in Baden-Württemberg and low-protein feeding of pigs in Lower Saxony, the benefits of greenhouse gas emission reductions are even higher than those of NH_3 and PM emission abatement, although the measures focus on NH_3 and PM emission abatement. A diet shift has broad benefits for air pollution, greenhouse gas reduction and biodiversity conservation, additional dietary health benefits of low meat consumption, and opens scope for alternative use of arable land for food supply or lignocellulosic biomass production.

The findings in this thesis provide a better understanding of interactions among NH_3 and PM emission abatement and greenhouse gas emissions. They indicate that these interactions need to be included in the assessment of NH_3 and PM emission abatement measures and that a suitable approach that can depict such interactions needs to be chosen. The cost-benefit analysis carried out in this thesis proved to be a feasible and appropriate tool for the assessment of NH_3 and PM emission abatement measures, particularly in the presence of interactions with greenhouse gas emissions. The benefit estimates allow to identify the contribution of the benefits of each emission type to the total benefits. This fraction can be used to allocate the total abatement costs per measure to the specific emission types that were affected by the respective measure. This thesis shows that allocating the abatement costs to all emission types reduced instead to only one emission type decreased the abatement costs per emission type for synergetic measures. Such interactions and cost allocations should also be considered in the design of air quality and climate policies. They should be harmonised to avoid technologies that reduce air pollution but at the same time contribute to climate change, and vice versa, and to benefit from synergies.

The implementation of technical abatement measures in general comes at costs for farmers, whereas the whole society benefits from it, and is not expected to happen voluntarily. This suggests for policy that the implementation needs to be supported, e.g. by financial incentives. This could be done by a closer integration of agricultural and environmental policies in the EU Common Agricultural Policy. Diet shifts could be stimulated by nutrition information and discounting of plant-based products. Not only farmers are responsible for emission abatement, but also the whole society can contribute to emission reductions with their food choices.

This thesis has illustrated the importance of explicitly considering effects of NH_3 and PM emission abatement on greenhouse gases in the assessment and in environmental policy design, of including both cost and benefits in the assessment and of regarding diet shifts as complementary to technical abatement measures.

6.1.6 Recommendations for future research

The next steps in this research area may be to analyse combinations of technical emission abatement measures and variations of diet shifts together to develop overall cost-efficient NH_3 and

PM emission abatement strategies. As it was already argued above that the market effects of technical emission abatement measures and diet shifts were not adequately addressed in this thesis research, such an assessment should also explore wider economic impacts of the implementation of technical abatement measures and particularly of diet shifts. This could be done coupling agricultural emission models with an agricultural partial equilibrium model. Such a model can depict changes in food demand and subsequent indirect effects on food supply caused by changes in equilibrium prices. Depending on the trade specifications in the partial equilibrium model, it can depict effects on agricultural production outside the study region.

In this thesis, uncertainties related to impacts and monetary valuation were identified. Reducing the uncertainties of impacts requires more epidemiological studies related to health effects of changes in PM concentration and the influence of co-emitted pollutants. Also the health effect of the nitrates fraction and the sulphate fraction among secondary particles need to be investigated in more detail. Few studies quantify the impacts of N deposition and land use change on biodiversity, and they are related to specific locations. More studies in different natural conditions could reduce the uncertainty related to the transfer of indicators for biodiversity loss. In this context, also more studies for the monetary valuation of biodiversity loss would be useful.

Eventually, the analysis may be extended to include more emission types such as nitrates, nitrogen oxide and phosphorus and their environmental impacts in the assessment. They also cause damages to human health and biodiversity. Reducing them would reduce the average damage costs per emission type and increase the total benefits and may have synergies with NH_3 emissions abatement.

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Summary

In the past decades, agricultural and particularly livestock production have increased with population growth and increasing demand for food, especially for livestock products, at global level. This trend is expected to continue in the coming decades and may even be fortified by an increasing demand for non-food biomass in an economy based on renewable biological resources. Agriculture influences also the state of the environment. Agriculture has been associated with expansion into natural ecosystems, adversely affecting biodiversity and has a large share in the global emissions of greenhouse gases and ammonia (NH_3) and in the release and formation of primary and secondary fine particulate matter ($PM_{2.5}$). NH_3 emissions can lead to a loss of biodiversity in nitrogen-limited terrestrial ecosystems and can form secondary $PM_{2.5}$ in the atmosphere. $PM_{2.5}$ emissions may affect human health by causing respiratory and cardiovascular diseases and a reduction in life expectancy. As NH_3 and PM emissions partly originate from the same production activities as greenhouse gases, interactions between NH_3 and PM emission abatement and greenhouse gas emissions may exist. Emissions can be reduced by technical measures or by shifts towards a diet low in animal-based food products, because plant-based food products cause fewer emissions than animal-based food products.

In Germany, agriculture contributes about 95% of the total NH_3 emissions and 5% to primary $PM_{2.5}$ and 8% to greenhouse gas emissions. Because of the environmental impacts and subsequent governmental regulations, there is a need to reduce emissions of NH_3, $PM_{2.5}$ and of greenhouse gas emissions significantly. However, emission abatement is not without cost to farmers, and there is a significant regional variation in emissions, agricultural systems and in environmental conditions, which makes emission abatement challenging.

The main objective of the research described in this thesis was to increase the understanding of the full effects of NH_3 and PM emission abatement in agriculture, particularly to quantify and compare farmers' costs and society's benefits of reducing NH_3 and PM emissions in agriculture in Germany while considering interactions with greenhouse gas emissions and to identify cost-efficient NH_3 and PM emission abatement measures. Both technical NH_3 and PM emission abatement measures and a diet shift were examined with respect to the abatement costs and the benefits in terms of avoided damage costs of impacts on human health, terrestrial biodiversity and the climate. The analysis combined agricultural emission modelling and integrated environmental impact assessment, applying the impact-pathway approach, complemented by literature analysis.

Chapter 2 detailed the cost-benefit approach applied in this thesis to assess emission abatement measures in agriculture regarding farmers' abatement costs and society's benefits for human health

damages and terrestrial biodiversity in a case study for NH_3 emission abatement in Lower Saxony, Germany. Lower Saxony, a Federal State in the Northwest of Germany, has the highest livestock density in Germany and high ammonia emissions. The approach for estimating benefits applied the impact-pathway chain that traces air pollutants from their source along the dispersion and conversion in the atmosphere to the affected receptors, e.g., the human population and ecosystems, and combined it with a monetary valuation of physical impacts. The emissions, the abatement potentials and farmers' abatement costs were estimated based on results of the bioeconomic farm model EFEM[9]. The physical impacts and damage costs were estimated with the integrated environmental assessment model EcoSense. The study analysed various manure storage cover and manure application techniques at the farm level. The NH_3 emission reductions ranged from 2 to 25%. Farmers' average abatement costs ranged from 2.0 to 17 EUR per kilogramme NH_3 reduced depending on the farm type. The average benefits were 24.5 EUR per kilogramme of NH_3 reduced and exceeded the abatement costs in all cases.

In chapter 3, abatement measures for NH_3 and PM emissions were analysed including their interactions with greenhouse gas emissions. Abatement costs and benefits were derived in case studies for the German Federal States of Brandenburg, Baden-Württemberg and Lower Saxony. The bioeconomic farm model EFEM and the integrated environmental assessment model EcoSense were combined and the approach presented in chapter 2 was applied to abatement measures in livestock and crop production. The abatement measures in livestock production comprised feeding strategies, manure storage and application techniques and exhaust-air purification. The abatement measures in crop production were conservation tillage and the substitution of urea fertiliser. All NH_3 and PM emissions abatement measures interacted with greenhouse gas emissions. Exhaust air purification with chemical washers, manure application with injection or cultivator and manure storage with concrete cover achieved the highest net benefits in Lower Saxony (156 to 261 million EUR). Conservation tillage reduced both PM emissions and, by sequestering soil organic carbon, greenhouse gases and increased farmers' gross margins yielding high net benefits particularly in Baden-Württemberg (197 million EUR). The results confirmed interactions between air pollutant abatement and climate change mitigation in agriculture and suggested that they be integrated in an analysis to identify synergies.

Chapter 4 complemented the analyses of technical emission abatement measures by an analysis of changes in food consumption patterns and food production and their impacts on human health and the environment in the European Union. The high intake of meat, dairy products and eggs caused

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[99] Beletskaya, O. (2016): Modelling of particulate matter and ammonia emissions from German agriculture. Dissertation, University of Hohenheim, Stuttgart.

intake levels of saturated fats and red meat that exceed dietary recommendations and therefore the consumption of animal-based food should be reduced. By applying biophysical models such as MITERRA, a 50% reduction in animal-based food consumption in the EU, balanced by plant-based food consumption, was analysed. Assuming corresponding changes in agricultural production, the diet shift reduced nitrogen and greenhouse gas emissions by up to 40% and the per capita use of cropland by 23% that provided scope for alternative uses of land such as for additional food production for export or a production of perennial bioenergy crops combined with extensive grassland production. The intake of saturated fats was reduced by 40%, which was expected to lead to a reduction in cardiovascular mortality. The results suggested that human diets low in animal-based food products were beneficial both for human health and for the environment.

The analysis of impacts of changes in food consumption and production on the environment carried out in chapter 4 was further developed and applied to Germany in chapter 5. A 50% reduction in animal-based food consumption, balanced by plant-based food consumption, and corresponding changes in food production, freed up 23% of cropland and 33% of grassland in Germany. In three land use scenarios, the potentials for (i) additional export cereal production, (ii) lignocellulosic biomass production for energy or material use and (iii) biodiversity conservation by maintaining and extensifying grassland and setting-aside arable land were explored and their impacts on emissions of NH_3, $PM_{2.5}$ and greenhouse gases were analysed. NH_3 emissions were reduced by 39 to 45%, $PM_{2.5}$ emissions by 25 to 38% and greenhouse gases by 34 to 40%. The damage costs of biodiversity loss caused by NH_3 emissions were reduced by 18 to 44% and of human health caused by NH_3 and $PM_{2.5}$ emissions, by 38 to 44%. The damage costs of greenhouse gases were reduced by 18 to 59%. In total, damage costs were reduced by 5,275 to 7,650 million EUR. The agricultural sector lost 2 to 9% (690 to 3,130 million EUR) of its income. The private household expenditure for food was reduced by 6% (8,300 million EUR). In all scenarios, the benefits exceeded the agricultural income loss and the benefit-to-cost ratios ranged from 2.3 to 7.7. The analysis of impacts on emissions was complemented by an analysis of impacts of land use change on biodiversity with the approach of Environmental Damage Potentials and subsequent monetary valuation. Including this aspect in the overall evaluation of the scenarios, the results indicated that arable land freed-up from livestock production should be cultivated with food crops or with lignocellulosic biomass for material use while grasslands should be maintained and extensified.

Chapter 6 synthesised the findings of the research chapters 2 to 5 and discussed them in relation to the research questions. The cost-benefit-approach based on the impact-pathway chain with subsequent monetary valuation of physical damages proved to be a feasible and useful tool, particularly in the light of interactions among NH_3 and PM emission abatement and greenhouse gas mitigation where the monetary values served as the common indicator for comparison. The abatement potentials ranged from 2 to 45% for NH_3 emissions, from 0 to 38% for $PM_{2.5}$ emissions and from 0to 49% for greenhouse gas emissions. The abatement potentials of a diet shift exceeded those of technical abatement measures. All air pollutant abatement measures affected greenhouse gases, in most cases synergistically. The average abatement costs ranged from 2.7 to 25.6 EUR per kilogramme NH_3 reduced, from 7.5 to 31.2 EUR per kilogramme $PM_{2.5}$ reduced and 0.01 to 0.03 EUR per kilogramme greenhouse gas emissions reduced. The average benefits were 24.5 EUR per kilogramme NH_3 reduced and 68.3 EUR per kilogramme $PM_{2.5}$ reduced. The benefits of reduced health damage costs were higher than those of reduced biodiversity loss, resulting in higher benefits of $PM_{2.5}$ reduction. The benefits of the reduction of greenhouse gas emissions were 0.09 EUR per kilogramme. In conclusion, synergies with greenhouse gas mitigation reduced the abatement costs per unit of emission type, increased the benefits and improved the cost-efficiency of air pollutant abatement measures. This finding indicates that air pollutant abatement and greenhouse gas mitigation should be analysed together and that environmental policy design should consider interactions. The abatement potentials of technical measures were limited and should be complemented by changes in food consumption patterns to meet politically agreed emission reduction targets. Besides emission reductions, diets with low consumption of animal-based food provided land for alternative uses such as food production, lignocellulosic biomass production or biodiversity conservation that have the potential to reduce pressure on land from increasing demand for food by a globally growing population or for lignocellulosic biomass in an economy based on renewable biological resources.

Zusammenfassung

In den letzten Jahrzehnten hat die landwirtschaftliche Produktion, insbesondere die Tierproduktion, mit wachsender Weltbevölkerung und der damit verbundenen gestiegenen Nachfrage nach Lebensmitteln, insbesondere nach tierischen Produkten, auf globaler Ebene zugenommen. Es ist zu erwarten, dass sich diese Entwicklung in den kommenden Jahrzehnten fortsetzt und aufgrund der zunehmenden Nachfrage nach landwirtschaftlicher Biomasse für die stoffliche und energetische Nutzung in einer Bioökonomie sogar verstärkt. Die landwirtschaftliche Produktion ist mit Umweltwirkungen verbunden. Die Landwirtschaft wird mit der Ausdehnung ihrer Flächen in natürliche Ökosysteme und daraus folgendem Verlust an Biodiversität in Verbindung gebracht. Zudem verursacht die Landwirtschaft einen erheblichen Anteil an anthropogenen Treibhausgasemissionen, Ammoniakemissionen (NH_3) und der Emission und Bildung von primärem und sekundärem Feinstaub ($PM_{2.5}$). NH_3-Emissionen können einerseits zu einem Verlust an Biodiversität in Stickstoff-limitierten terrestrischen Ökosystemen führen und andererseits in der Atmosphäre sekundären Feinstaub bilden. Feinstaub kann die menschliche Gesundheit beeinträchtigen, indem er Atemwegserkrankungen sowie Herz-Kreislauf-Erkrankungen verursacht und zu Lebenszeitverkürzung führt. Da NH_3- und Feinstaubemissionen teilweise aus den gleichen landwirtschaftlichen Produktionsaktivitäten stammen wie Treibhausgase, besteht möglicherweise ein Einfluss von Maßnahmen zur Reduktion von NH_3- und Feinstaubemissionen auf Treibhausgasemissionen.

Die Emissionen können einerseits mit technischen Maßnahmen reduziert werden. Andererseits könnte auch eine Umstellung der menschlichen Ernährung zu einer Ernährungsweise mit einem geringeren Verzehr von tierischen Produkten und einem höheren Verzehr von pflanzlichen Produkten zur Reduktion von Emissionen führen, weil pflanzliche Lebensmittel weniger Emissionen verursachen als tierische Produkte.

In Deutschland stammen etwa 95% der NH_3-Emissionen, 5% der primären Feinstaubemissionen und 8% der Treibhausgasemissionen aus der Landwirtschaft. Aufgrund ihrer schädlichen Auswirkungen auf Umwelt und Gesundheit wird auf politischer Ebene ihre deutliche Reduktion gefordert. Jedoch ist die Minderung der Emissionen in der Regel mit Vermeidungskosten für die Landwirtschaft verbunden. Zudem besteht eine hohe regionale Variation an Emissionen, landwirtschaftlichen Produktionssystemen und Umweltzuständen, was für die Reduktion von Emissionen eine Herausforderung darstellt.

Das Hauptziel dieser Dissertation war, den Stand des Wissens bzgl. umfassender Effekte der Reduktion von NH_3- und Feinstaubemissionen in der Landwirtschaft zu verbessern. Insbesondere

war das Ziel, die Vermeidungskosten für die Landwirtschaft und den Nutzen für die Gesellschaft in Deutschland unter der Berücksichtigung von Auswirkungen auf Treibhausgasemissionen zu quantifizieren und kosteneffiziente Maßnahmen zur Minderung von NH_3- und Feinstaubemissionen zu identifizieren. In die Analyse wurden sowohl technische Maßnahmen als auch eine Änderung der Ernährungsweise einbezogen. Die Maßnahmen wurden hinsichtlich der Vermeidungskosten und dem erzielbaren Nutzen in Form von vermiedenen Schadenskosten bewertet. Dabei wurden Schäden an menschlicher Gesundheit, terrestrischer Biodiversität und Klima berücksichtigt. Hierzu wurden Modellanalysen durchgeführt, die durch Literaturanalysen ergänzt wurden.

Kapitel 2 beschreibt die Vorgehensweise zur Kosten-Nutzen-Analyse, die in dieser Dissertation angewandt wurde. In einer Fallstudie für die Tierproduktion in Niedersachsen wurden technische Minderungsmaßnahmen hinsichtlich den Vermeidungskosten für die Landwirtschaft und dem Nutzen für die Gesellschaft in Form von vermiedenen externen Kosten von Gesundheitsschäden und dem Verlust an terrestrischer Biodiversität analysiert. Niedersachen hat die höchste Tierbesatzdichte in Deutschland sowie hohe NH_3-Emissionen. Die Abschätzung des Nutzens basiert auf dem Wirkungspfadansatz. Dieser verfolgt die Emissionen auf ihrem Weg von der Quelle über die Ausbreitung und Umwandlung in der Atmosphäre zu den betroffenen Rezeptoren wie beispielsweise die Bevölkerung und Ökosysteme und ermittelt die physischen Wirkungen. Diese werden anschließend monetär bewertet. Die Emissionen, Vermeidungspotentiale und -kosten basieren auf Modellrechnungen, die mit dem umweltökonomischen landwirtschaftlichen Betriebsmodell EFEM durchgeführt wurden[10]. Die physischen Wirkungen und Schadenskosten wurden mit dem integrierten Umweltbewertungsmodell EcoSense ermittelt. In der Fallstudie wurden verschiedene Maßnahmen zur Güllelagerabdeckung und zur Gülleausbringung auf Ebene der landwirtschaftlichen Betriebe untersucht. Die Vermeidungspotentiale lagen zwischen 2% und 25%. Die durchschnittlichen Vermeidungskosten betrugen 2 EUR bis 17 EUR je Kilogramm reduzierten NH_3-Emissionen. Der Nutzen lag bei 24,5 EUR je Kilogramm reduzierten NH_3-Emissionen und damit in allen Fällen über den betrieblichen Vermeidungskosten.

In Kapitel 3 werden Maßnahmen zur Minderung von NH_3- und Feinstaubemissionen unter Berücksichtigung von möglichen Wechselwirkungen auf Treibhausgasemissionen untersucht. In drei Fallstudien für die Bundesländer Brandenburg, Baden-Württemberg und Niedersachsen wurden Vermeidungskosten und Nutzen ermittelt. Dazu wurde der in Kapitel 2 vorgestellte Ansatz verwendet und das landwirtschaftliche Betriebsmodell EFEM mit dem Umweltbewertungsmodell EcoSense kombiniert. Die Analyse umfasste technische Maßnahmen zur Emissionsminderung in

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der Tierproduktion und im Ackerbau. Die Minderungsmaßnahmen in der Tierproduktion waren proteinreduzierte Fütterung, Güllelagerabdeckungen und Gülleausbringungsmaßnahmen sowie Abluftreinigung. Die Minderungsmaßnahmen in der Pflanzenproduktion waren konservierende Bodenbearbeitung und die Substitution von Harnstoffdünger. Alle Maßnahmen zur Minderung von NH_3- und Feinstaubemissionen wirkten sich auch auf Treibhausgase aus. Beispielsweise verringerte reduzierte Bodenbearbeitung sowohl Feinstaubemissionen als auch – durch die Bindung von Kohlenstoff im Boden – Treibhausgasemissionen. Zudem stieg das landwirtschaftliche Einkommen, wodurch diese Maßnahme vor allem in Baden-Württemberg einen hohen Nettonutzen erbrachte (197 Millionen EUR). Überdies erzielten auch chemische Wäscher zur Abluftreinigung, Gülleausbringung mit Injektionstechniken und Güllelagerabdeckung mit Betondecken sehr hohe Nettonutzen (156 bis 261 Millionen EUR). Die Ergebnisse bestätigten, dass positive Wechselwirkungen zwischen Luftreinhaltung und Klimaschutz in der Landwirtschaft bestehen. Daraus lässt sich schlussfolgern, dass eine integrierte Analyse sinnvoll ist, um Synergien bei der Emissionsreduktion zu identifizieren.

Die Bewertung der technischen Maßnahmen wurde im 4. Kapitel durch die Analyse einer Änderung der Ernährungsweise und der Lebensmittelproduktion und der damit verbundenen Auswirkungen auf die menschliche Gesundheit und die Umwelt, wie z. B. Landnutzung und Stickstoffemissionen, in der Europäischen Union ergänzt. Es wurde gezeigt, dass der hohe Verzehr von Fleisch, Milchprodukten und Eiern in der Europäischen mit einer hohen Aufnahme von gesättigten Fetten und rotem Fleisch verbunden ist und deutlich über den Empfehlungen für gesunde Ernährung liegt. Deshalb sollte der Verzehr von tierischen Produkten verringert werden. Unter Anwendung von biophysikalischen Modellen wie MITERRA wurde eine Halbierung des Konsums von tierischen Produkten analysiert, der durch einen höheren Verzehr von pflanzlichen Produkten auf Energiebasis kompensiert wurde. Unter der Annahme, dass die Änderung im Verzehr zu einer proportionalen Änderung in der landwirtschaftlichen Produktion führt, wurden Stickstoffemissionen und Treibhausgasemissionen um bis zu 40% reduziert. Der Pro-Kopf-Verbrauch von Ackerland ging um 23% zurück. Die freigewordenen Flächen wurden zum Anbau von zusätzlichen Nahrungsmitteln oder von mehrjährigen Bioenergiepflanzen mit einer Extensivierung der Grünlandproduktion genutzt. Der Verzehr von gesättigten Fetten wurde um 40% reduziert, was zu einer Reduktion von Herz-Kreislauferkrankungen führen könnte. Die Ergebnisse verdeutlichen, dass eine Ernährungsweise mit einem verringerten Verzehr von tierischen Produkten sowohl gut für die Gesundheit als auch für die Umwelt ist.

Die in Kapitel 4 durchgeführte Analyse wurde in Kapitel 5 weiterentwickelt und auf Deutschland angewandt. Eine Halbierung des Konsums von tierischen Produkten, der durch einen höheren

Verzehr von pflanzlichen Produkten auf Energiebasis ausgeglichen wird, und entsprechende Änderungen in der landwirtschaftlichen Produktion, führten zu einem um 23% geringeren Bedarf and Ackerfläche und zu einem um 33% geringeren Bedarf an Grünlandfläche in Deutschland. In drei Szenarien zur Landnutzung wurden die Potentiale für (i) den zusätzlichen Anbau von Exportgetreide, (ii) den Anbau von Lignozellulose-Biomasse für die stoffliche oder energetische Nutzung und (iii) den Biodiversitätsschutz durch Grünlanderhalt und Extensivierung sowie langfristig angelegte Brachflächen untersucht und ihre Auswirkungen auf die Emissionen von NH_3, Feinstaub sowie Treibhausgasen analysiert. Die Reduktion von NH_3-Emissionen lagen zwischen 39% und 45%, von Feinstaub zwischen 25% und 38% und von Treibhausgasen zwischen 34% und 40%. Die Schadenskosten für den Verlust an terrestrischer Biodiversität, der durch NH_3-Emissionen verursacht wurde, gingen um 18% bis 44% zurück. Die Kosten für die durch NH_3- und Feinstaub-Emissionen verursachten Gesundheitsschäden gingen um 38% bis 44% zurück. Die durch Treibhausgase verursachten Schadenkosten wurden um 18% bis 59% reduziert. Insgesamt gingen die Schadenkosten um 5.275 bis 7.560 Millionen EUR zurück. Durch die Änderungen in der landwirtschaftlichen Produktion in Deutschland ging das landwirtschaftliche Einkommen um 2% bis 9% (690 bis 3.130 Millionen EUR) zurück. Die Änderung der Ernährungsweise führte bei den Privathaushalten zu einem Rückgang der Ausgaben für Lebensmittel um 6% (8.300 Millionen EUR). In allen Szenarien war der Nutzen der vermiedenen Umwelt- und Gesundheitsschäden größer als der Einkommensrückgang in der Landwirtschaft, wodurch sich positive Nettonutzen ergaben. Das Nutzen-Kosten-Verhältnis lag zwischen 2,3 und 7,7. Neben den Auswirkungen auf die Emissionen wurden ergänzend die Auswirkungen von Landnutzungsänderungen auf die Biodiversität mit dem *Environmental-Damage-Potential*-Ansatz betrachtet und monetärer bewertet. Wenn dieser Aspekt in der Beurteilung der Landnutzungsszenarien berücksichtigt wird, ergibt sich, dass Ackerland mit Nahrungsmitteln oder Biomasse für die stoffliche Nutzung bebaut und dass Grünland erhalten und ggf. extensiviert und in naturnahes Grünland umgewandelt werden sollte.

Im Kapitel 6 wurden die Ergebnisse der Forschungskapitel 2 bis 5 zusammengeführt und hinsichtlich der Forschungsfragen diskutiert. Es hat sich gezeigt, dass der Kosten-Nutzen-Ansatz auf Grundlage des Wirkungspfadansatzes mit monetärer Bewertung der Umweltschäden anwendbar und insbesondere hinsichtlich der Wechselwirkungen zwischen NH_3- und Feinstaubemissionen und Treibhausgasemissionen hilfreich war. Hier war der monetäre Wert der Schäden der gemeinsame Indikator, der einen Vergleich der unterschiedlichen Schäden ermöglichte. Die technischen Vermeidungspotentiale für NH_3-Emissionen lagen zwischen 2% und 27%, für Feinstaubemissionen zwischen 0% und 30% und für Treibhausgase zwischen 0% und

18%. Die Vermeidungspotentiale von Änderungen der Ernährungsweise und der Nahrungsmittelproduktion lagen für NH_3-Emissionen zwischen 39% und 45%, für Feinstaubemissionen zwischen 25% und 38% und für Treibhausgasemissionen zwischen 18% und 49%. Alle Vermeidungsmaßnahmen wirkten sich auf Treibhausgase aus; in den meisten Fällen konnten Synergien festgestellt werden. Die durchschnittlichen Vermeidungskosten betrugen 2,7 EUR bis 25,6 EUR je Kilogramm NH_3-Emissionen, 7,5 EUR bis 31,2 EUR je Kilogramm Feinstaubemissionen und 0,01 EUR bis 0,03 EUR je Kilogramm Treibhausgasemissionen. Der Nutzen für die Reduktion von NH_3-Emissionen lag bei 24,5 EUR je Kilogramm und bei 68,3 EUR je Kilogramm Feinstaub. Der höhere Nutzen bei der Reduktion von Feinstaubemissionen ging auf die im Vergleich zum Biodiversitätsverlust durch NH_3-Emissionen höher bewerteten Gesundheitsschäden zurück. Der Nutzen für die Reduktion von Treibhausgasen betrug 0,09 EUR je Kilogramm. Mit Ausnahme von wenigen technischen Maßnahmen waren alle Maßnahmen kosteneffizient. Synergien mit Treibhausgasemissionen reduzierten die Vermeidungskosten je Emissionsart, erhöhten den Nutzen und verbesserten die gesamte Kosteneffizienz der Luftreinhaltemaßnahmen. Auf Grundlage der Ergebnisse lässt sich schlussfolgern, dass Luftreinhaltemaßnahmen in der Landwirtschaft mit ihren Auswirkungen auf Treibhausgasemissionen gemeinsam analysiert und dass Wechselwirkungen zwischen Luftreinhaltung und Klimaschutz bei der Politikgestaltung berücksichtigt werden sollten.

Die Potentiale der technischen Minderungsmaßnahmen sind begrenzt und sollten durch eine Änderung der Ernährungsweise ergänzt werden, um politisch vorgegebene Reduktionsziele zu erreichen. Zusätzlich zu den Emissionen reduzierten Ernährungsweisen mit geringem Verzehr von tierischen Produkten den Verbrauch an landwirtschaftlicher Fläche. Die von der Tierproduktion nicht mehr benötigte Fläche kann alternativ verwendet werden wie beispielsweise für die Produktion zusätzlicher Nahrungsmittel oder von Lignozellulose-Biomasse, oder die landwirtschaftliche Produktion kann zur Verbesserung der Biodiversität extensiviert werden. Zudem hat der geringere Flächenbedarf das Potential, den Druck auf die Landnutzung, der aus der steigenden Nachfrage nach Lebensmitteln durch die wachsende Weltbevölkerung oder nach Lignozellulose-Biomasse in einer Bioökonomie resultiert, zu verringern.