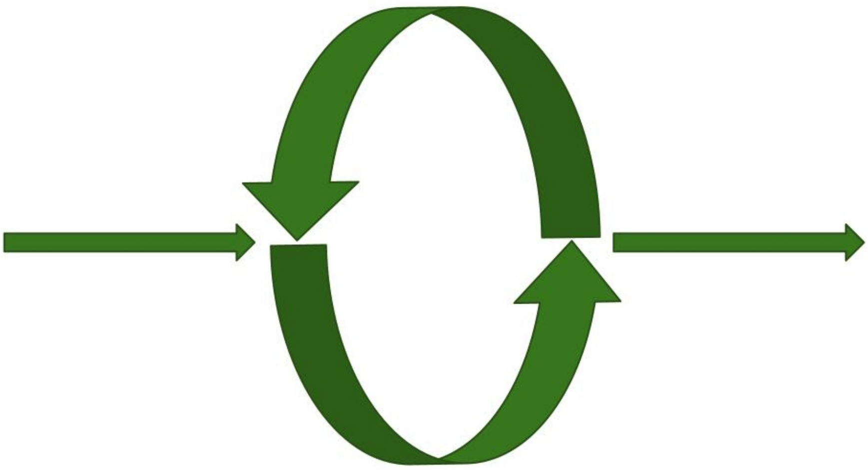

Towards closing the nitrogen flow in UK agriculture

An explorative study of integrated food and bioenergy production with increased nitrogen recirculation

Master of Science Thesis in the Master Degree Programme, Industrial Ecology - for a sustainable society

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Division of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

Master's Thesis FRT 2011:02

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Cover:
Illustration of the concept of increased nutrient recirculation that is applied in the thesis

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Abstract

Nitrogen is an essential growth factor in nature and for food production. It exists in many forms, including reactive nitrogen compounds available for plant uptake, that can cause environmental impacts in high concentrations. Large amounts of reactive nitrogen in fertilisers are applied to crop areas, and the anthropogenic use of reactive nitrogen has increased manifold during the last century. Nitrogen in harvest residues and animal manure is recycled to crop fields inefficiently, and the overall flow of nitrogen through agriculture is practically linear, with substantial losses to air and water. Policies regulate some nitrogen practices, but seem not to provide a strong incentive for recycling. A more closed flow of reactive nitrogen within agriculture and the rest of society could reduce the need for nitrogen fertilisers, and also reduce environmental impacts caused by nitrogen leaching, notably eutrophication of aquatic ecosystems.

Pressure is also put on agriculture to meet the increased demand for bioenergy. Increased production of cellulosic bioenergy crops can, in this context, have a positive effect on the environmental performance of agriculture, and can in several ways be part of strategies for obtaining a more closed flow of nitrogen in the socio-agricultural system.

This thesis develops and models an alternative agricultural system, with increased nitrogen recirculation. Cultivation of cellulosic bioenergy crops are integrated into the food production to provide nitrogen leaching interception. These biomass production systems are combined with nitrogen recycling. Livestock are fed more efficiently than in the current system. Manure is collected and treated through anaerobic digestion for production of biogas and stabilisation of volatile nitrogen. Analyses using a model representation of the alternative agricultural system show that these measures substantially improve the recycling of nitrogen in the system, reduce the losses and decrease the need for chemical fertiliser input. The thesis concludes that implementation of certain bioenergy options that enhance nitrogen recycling can give an important contribution to closing the nitrogen flow in agriculture. A second conclusion is that a systems perspective on nitrogen is essential for implementation of policies promoting an increased nitrogen recycling within the socio-agricultural system.

Keywords: nitrogen recycling, agriculture, cellulosic, bioenergy, anaerobic digestion, nitrogen leaching, biofuel, willow, buffer strips, model

Preface

This diploma project was arranged in collaboration with Dr Jeremy Woods, Imperial College, London, and Dr Göran Berndes, Chalmers University of Technology, Göteborg. The thesis was developed and carried out by the author as part of the master degree programme in Industrial Ecology.

Thanks to Dr Jeremy Woods for supervision, inspiring meetings and arranging the hosting at Imperial College. Thanks to Dr Göran Berndes for co-supervision and important perspectives, as well as for being examiner and help with funding. This thesis would not have been possible without you both. Also thanks to Imperial College doctoral researchers Arturo Castillo-Castillo and Alexandre Strapasson for valuable comments and interesting discussions throughout the project.

It was a challenge to compile a linear report from an intertwined circular topic.

Sara Alongi Skenhall, Göteborg, June 2011

Contents

1 Introduction

1.1 Background

The background to this report is a degree project carried out in the field of Industrial Ecology. The thesis explores options to close the flow[1] of nitrogen in the agricultural system, to reduce losses and input, by focusing on nitrogen recycling and integration of cellulosic bioenergy crops into the agricultural production landscape.

Nitrogen is not a scarce element, but instead abundant in the atmosphere on Earth. It is scarce in terrestrial and aquatic ecosystems, and therefore an essential growth factor in nature and for food production. Nitrogen forms many reactive compounds that in excessive concentrations are environmental pollutants. The anthropogenic use of reactive nitrogen in agriculture has increased during the last century's industrialisation of agriculture in the developed world. The flow of nitrogen through agriculture today is linear. Large amounts of reactive nitrogen in fertilisers are applied to crop areas and grassland, with substantial losses to air and water. Nitrogen in animal waste is recycled to crop fields inefficiently. Nitrogen in human waste is recycled to some extent, but often large efforts are made to transform reactive nitrogen into harmless nitrogen gas in wastewater treatment works. In the UK, nitrogen from human waste almost not recycled or transformed at all, but instead emitted to aquatic ecosystems. Therefore, there is a call for thinking more about recycling of reactive nitrogen, and a more closed flow of nitrogen in the socio-agricultural system could reduce environmentally costly input and losses.

Pressure is also put recently on agriculture to meet the increased demand for bioenergy. Bioenergy is an old renewable resource, that has gained popularity again during the discourse on climate change and energy security. Cellulosic bioenergy crops can have a positive impact on the environmental performance of agriculture and they can in several ways increase the nitrogen use efficiency of the production system. Such crops could therefore be part of trying to close the flow of nitrogen in the socio-agricultural system.

1.2 Purpose and Objective

The purpose of this thesis is to understand the following questions:

- How can the flow of nitrogen in agriculture be managed and closed to reduce the environmentally damaging losses, with maintained food and livestock production?
- What might the role of cellulosic bioenergy be in such a system?
- What are the recommendations for nitrogen-related policies?

The objective is to build a model of the agricultural system in the UK[2] with a more closed flow of reactive nitrogen.

[1] 'Close the flow' is an expression from Industrial Ecology, which means closing the loop, and is further explained in Section 2.4

[2] United Kingdom of Great Britain and Northern Ireland consisting of: England, Wales, Scotland and Northern Ireland

1.3 Scope

This thesis focuses on nitrogen as a pollutant and nutrient, and the large national flows of it in the socio-agricultural system in the UK. Other nutrients and their flows are not considered. The main focus is on preventing losses of the biologically reactive forms of nitrogen (nitrate, nitrite, ammonia, ammonium) and increase the recycling of them. Nitrous oxide emissions mitigation is not included. The model is built for the agriculture in the UK, but the concept may be applicable to other industrialised agricultural systems as well. The model handles today's agriculture with nitrogen flow management measures implementable in the medium term. The model has a national systems perspective, and therefore local or regional arrangements or soil conditions are not considered. Erosion, soil carbon, biodiversity, and nitrous oxide emissions from soil is only touched upon. Forestry and forest products are not included in the concept of bioenergy in this thesis. The output from agriculture is modelled to be the same as today, and no future increases or changes in demand are taken into account. Agricultural non-food goods such as wool or leather are not included, neither are economic costs or energy use by agricultural practices. The system boundary is around the agriculture within the UK, and so import/export of food products are not considered.

1.4 General method

The thesis has been developed under an extensive literature and scoping study on nitrogen and agricultural practices such as nitrogen management and cropping alternatives. The study also investigated cellulosic bioenergy and its potential role in emissions mitigation from agriculture as well as land use under the increased concern for food and energy security. The concept of a nitrogen efficient socio-agricultural system was developed based on the theory of substance flows and dematerialisation from the field of Industrial Ecology. The project set out to create an agricultural system with a more closed flow of nitrogen, with UK as an example.

Information and data on crop production and livestock were collected for agriculture in the UK and assembled into a simplified model system. Recycling technologies were investigated and added to the model, as well as the leaching interception module on cropland by perennial bioenergy crops. The agricultural system was slightly modified to allow for closing of the flow, but is based on today's output of food products to meet the demand. Forage feedstocks for cattle were changed. Land areas were allowed for bioenergy production to reflect the current interest in renewable energy and biofuels. The flows of nitrogen through agriculture were quantified and rearranged to the alternative model system. Finally, a sensitivity analysis was made of the assumptions around technology implementation and production arrangement, and their influence on the system flows of nitrogen. Details about how the model was built and the assumptions made are available primarily in Section 3, but also together with calculations in Appendix A and B.

2 Problem description and potential solutions

This theory chapter presents the parts from the initial literature study, that are relevant for the project. Nitrogen's role in nature and the anthropogenic influences are followed by a description of nitrogen in agriculture and current agricultural practices in the UK. A review of bioenergy and its potential role in agriculture is presented. The chapter ends with tying the parts together by conceptualising the problem into terms of resource flows, and how the problem is transformed into the project task.

2.1 Nitrogen: an essential environmental pollutant

2.1.1 Nitrogen in nature

On Earth, nitrogen (N) is present in both the lithosphere, biosphere and atmosphere. The largest reservoir is the atmosphere where nitrogen resides mainly as nitrogen gas (N_2), but also to some extent as nitrous oxide (N_2O). N_2 is inert and an environmentally harmless form of nitrogen. N_2O is relatively inert but a powerful greenhouse gas taking part in stratospheric ozone reactions together with other oxides of nitrogen. Nitrogen is an essential element in proteins and enzymes, thereby important for all life structures and functions. It is therefore a limiting growth factor in both terrestrial and marine ecosystems. Nitrogen can have many oxidation states, and forms several reactive compounds that are active in biological processes.[1, 2]

In the natural nitrogen cycle, nitrogen is fixed from the atmosphere by microorganisms that reduces N_2 to ammonia (NH_3), which is assimilated by plants and incorporated into organic structures in biomass. NH_3 can also be oxidised by microorganisms into nitrite (NO_2^-), and then further to nitrate (NO_3^-) in the nitrification process. NO_3^- is then assimilated by plants. Free NO_3^- in the soil is denitrified by microorganisms under anaerobic conditions, because the organisms need the oxygen in the nitrate. The nitrate is reduced to inert N_2 and released to air. If the reduction process is incomplete (for example if soil conditions changes), the nitrogen is released as N_2O. When dead organic material decomposes, nitrogen is mineralised into the soil as NH_4^+, and assimilated by other plants. Similar processes occur in the sea. Nitrogen can also be fixed non-biologically into nitrogen dioxide (NO_2) during thunderstorms in the atmosphere, oxidised and deposited as NO_3^- with rainfall.[1, 2, 3]

The assimilation and (de)nitrification processes are illustrated in Figure 1, which shows the natural flows and processes described above, together with the anthropogenic influences described in the next section.

2.1.2 A disturbed nitrogen cycle

Undisturbed, the nitrogen cycle experiences a dynamic equilibrium, where nitrogen flows through the ecosystem between its reservoirs. The human influence on the nitrogen cycle occurs mainly on two different parts of it, namely through high-temperature combustion processes and fertiliser production, both of them resulting in fixation of nitrogen into reactive forms such as NH_3, NO_3^-, NO and NO_2.

N_2 is non-biologically and *unintentionally* fixed during high-temperature combustion processes, i.e. burning of fuel in air, and oxidised into nitric oxide (NO) and nitrogen dioxide (NO_2), often termed together as NO_x gases. When biomass is burned, the nitrogen in the organic structures is also released as NO_x. In the air, NO_x is further oxidised and finally deposits as NO_3^- with rain, causing acidification and eutrophication in terrestrial and aquatic ecosystems. The extra inflow of nitrogen to the ecosystem can alter the balance between plants with different nitrogen demands, and therefore have an influence on biodiversity. The annual atmospheric deposition of nitrogen averages 17 kg_N per hectare in the UK and other European countries [4]. NO and NO_2 also have an influence on the formation of tropospheric ozone, which causes respiratory health problems in humans and damage to vegetation and crops.[1]

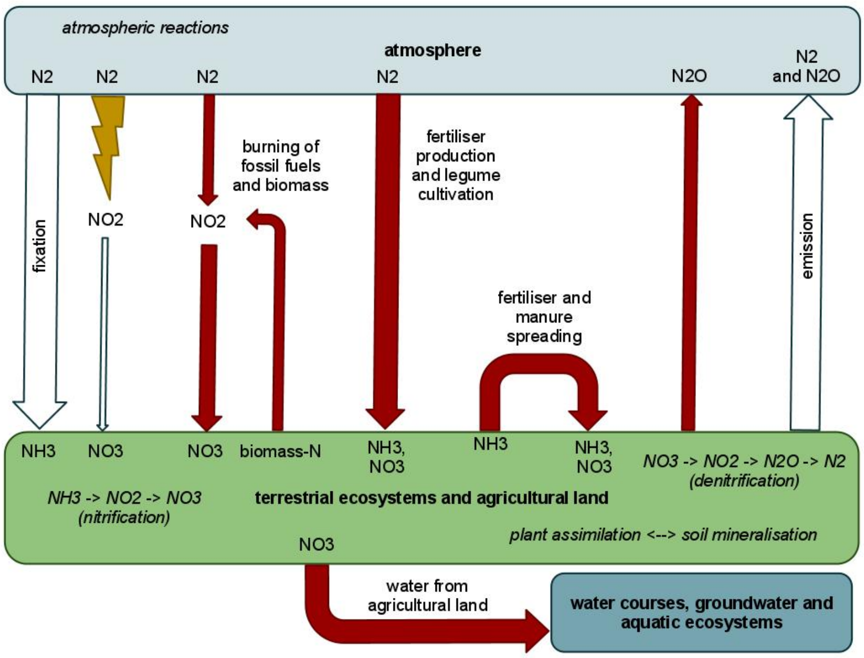

Figure 1: Schematic of the disturbed N-cycle with flows relevant for the thesis. White arrows = natural flows, red arrows = anthropogenically induced flows. Flows are not entirely to scale, but adjusted to give an indication of their interrelationship.

This thesis focuses on the second influence: the *intentional*, industrial-scale, fixation of N_2 through the Haber-Bosch process to produce nitrogen fertilisers for agriculture, in the form of ammonium (NH_4^+), ammonium-nitrate (NH_4NO_3), and urea ($(NH_2)_2CO$). There is also an anthropogenic influence through cultivation of nitrogen fixing legumes. When fertilisers (or manure) are applied to the crop field, ammonium may evaporate as NH_3 to air (volatilisation), and later deposit with wind or rain on other land or over the sea. Ammonia may also oxidise and deposit as nitrate with rainfall. Excess nitrate in the soil (both from nitrate and oxidised ammonia in the fertiliser) will be denitrified, maybe resulting in release of the greenhouse gas N_2O. However, since NO_3^- is highly soluble in water, most of the excess nitrate in the soil will leach away with rainwater. If the nitrate leaches away together with base cations (soil metals), the soil will suffer from acidification. Nitrate contaminates ground and surface water, and is toxic at high concentrations in drinking water. When the nitrate-rich water reaches watercourses and the sea, it acts as a fertiliser, causing overgrowth of algae. When there is an excess of dead algae to degrade, the water becomes *eutrophic*, i.e. depleted of dissolved oxygen.[1]

The formation of biologically reactive nitrogen through industrial fixation has increased manifold over the last century and humanity is disturbing the nitrogen fluxes on a global scale [5, 6]. The anthropogenic release of nitrogen to the terrestrial environment in now as large as all the natural sources together [7]. These increased fluxes affect climate, atmospheric chemistry and the functions of terrestrial and aquatic ecosystems [5]. Figure 1 illustrates part of the nitrogen cycle relevant for the thesis, with anthropogenic influences.

2.1.3 Nitrogen's special position

After sunlight and water, nitrogen is the most critical growth factor for plants [8]. However, it could be argued that other nutrients such as phosphorus (P), potassium (K) or sulphur (S) also are important. Phosphorus, for example, is a very important growth factor and an environmental pollutant causing eutrophication. While this is true, phosphorus differs from nitrogen by being in practically only one form in the environment (organic or inorganic as PO_4^{3-} with low solubility), mainly transported as dust, having no impact on climate and the absolutely largest reservoir being the stable and rather inaccessible lithosphere [1]. The problem with phosphorus is rather how to manage a *scarce* resource in a sustainable way. Other nutrients important for plants, and with important environmental effects, hold similar "simple" resource characteristics compared to nitrogen.

The range of environmentally harmful compounds that nitrogen forms, and the scale of the fixation and loss, shows the importance of focusing on the nitrogen flow, not as a scarce resource but rather as an abundant resource where careless use causes ecosystem degradation and climate change.

2.2 Agriculture: one cause of the problem

2.2.1 Emissions from agriculture

As mentioned in the previous section, fertiliser use can lead to large losses of nitrogen to the environment. Agriculture is therefore a large contributor to nitrogen-related environmental problems. Besides the large losses of nitrate to water and smaller losses of N_2O from soils, agriculture also contributes to climate change through emissions of CO_2 and N_2O in the (fossil) energy intensive and sometimes inefficient fertiliser production. Today, agriculture is globally responsible for nearly 12% of anthropogenic greenhouse gas emissions [9]. Most of the anthropogenic N_2O emissions comes from agriculture and considering that N_2O is a 300 times stronger greenhouse gas than CO_2 [10] makes the problem substantial. Agriculture is highly dependent on fossil resources for fuel and fertiliser production, being one of the reasons for the high contribution to greenhouse gas emissions from this sector. When demand for food increases, and thereby yields have to be increased by intensification, the high greenhouse gas emissions from this sector will most likely increase, if there is no switch to more efficient management practices and renewable energy sources [11].

2.2.2 Fertiliser use

Most soils are too poor in nitrogen to give the yields that are required in agriculture today, which is one of the reasons why fertilisers are so important. After the Second World War the use of industrial fertilisers grew sevenfold [12] globally during the "Green Revolution". This is one of the reasons that made the population growth since then possible [12]. However, constantly increased nitrogen application rate experiences diminishing returns on yield [8, 12]. It leads to high losses of reactive nitrogen to the environment, with subsequent environmental impact. The fertiliser use globally is also very inefficient with crop uptake efficiency of only 45-55% of the applied nutrients [8, 12, 13].

Chemical nitrogen fertiliser application amounted to about 1.1 million tonnes[3] in the UK in 2010 [14], which is about 1% of the global nitrogen fertiliser use [7]. The recent decades has seen a decline in chemical fertiliser use in the UK [15], with following decreased emissions of nitrous oxide and ammonia. There may be different reasons for the declined fertiliser use, such as increased fertiliser price due to higher oil price. It is also probably because of improved information to farmers about efficient nitrogen practices. Soil testing to match nutrient requirements in crops with fertiliser application is common today in the UK, it is used on 95% of the cereal farms [15], but other types of precision farming is not so widespread.

Controlled Release Fertilisers (CRF) are an alternative to conventional fertilisers, with the purpose of releasing plant nutrients in a controlled way, and timing with plant uptake to reach optimal yield [16]. They can be granules with coatings that release nitrogen depending on soil moisture or temperature. The fertiliser recovery in plants can be as high as 75% with this technique [16]. In-time-release of fertiliser can also decrease unwanted losses and emissions from soils that occur when excess nitrogen is denitrified into N_2O or lost through leaching [17]. CRFs are currently more expensive than conventional fertilisers, and mainly used for horticultural crops or in private gardens, but if the fertiliser need for the whole crop season can be applied at the time of seeding, total costs for the farmer could be decreased [8]. It is beyond the scope of this thesis to model this type of fertiliser. CRFs are promising for the future, but as long as they are produced from fossil energy sources, they contribute to the environmental problem associated with fertiliser use.

2.2.3 Manure spreading and losses

Chemical fertiliser figures do not include application of manure on crop fields and grassland in the UK, neither as applied nor as direct deposition from grazing

[3]Based on annual application rates of 149 and 63 kg_N per hectare on arable tillage crops and permanent grassland, respectively

livestock. DEFRA's[4] Fertiliser Survey [18] estimate that organic manures are applied on about 25% of the agricultural area and broadcasting is used by 80% of the farmers to spread the manure, after which incorporation often takes place within a week. These practices imply high losses of NH_3 from the field [19, 20, 21]. Although ammonia emissions have declined recently, it rather reflects the decreased livestock numbers [15].

Livestock animals excrete large amounts of manure, which is rich in ammonia and organic nitrogen. That is one of the reasons why cattle should not be overfed; to reduce the loss of nitrogen to manure [3]. Manure also contains organic material and is therefore beneficial for soil quality. Spreading of manure on arable land is an old and conventional practice, as it serves as a free and on-farm available fertiliser. However, if spreading practice and incorporation are poor, up to 80% of the ammonia can be lost through volatilisation [20, 21]. Manure deposition by grazing livestock is not mechanically incorporated into the soils and losses are therefore large. Manure application or deposition is also a large contributor to freshwater pollution through leaching from grazing land [7].

2.2.4 Soil dynamic, uptake and leaching

The soil dynamic is not completely understood. Soil organic matter (SOM) is an important component in how much nitrogen can be stored in the soil. The pool of plant-available nitrogen in the soil is controlled by soil microorganisms. These organisms rely on the SOM, that contains soil carbon. Modern agricultural soils with mono-cultures and high extraction of biomass from the fields by harvest have little SOM. In a system with low soil carbon, the microorganisms cannot process all the fertiliser applied to the soil and the soil is therefore prone to leaching. Fertilised crops take up around 50% of their nitrogen from SOM-particles [13]. Growing cover crops improves SOM, water holding capacity and the potential for an organic nitrogen pool, and can decrease leaching by over 40% compared to letting land lie bare [13].

The nitrogen uptake by plants and crops differ also due to other parameters such as fertiliser type, application rate, timing of application, soil condition and type, precipitation etc. A general estimate of crop nitrogen uptake efficiency is 45-55% globally [8, 12, 13], where the rest is lost to the environment. Little SOM can be one of the reasons for the low uptake of fertilisers in modern agriculture and requires annually high fertiliser rates to compensate for the losses.

The factors influencing N_2O emissions from soils is a complex matter that is not yet fully understood. This area has in the light of climate change begun to get more attention. Emissions are more prone to happen with high fertiliser rate but other conditions play a role for the activities of microorganisms, for example aerobic/anaerobic environment, moisture and temperature [22]. Concrete management advice will be difficult to provide before it is fully understood how field and SOM management can steer the microorganic processes to reach complete denitrification of nitrates [2]. Despite the importance of N_2O emissions as a climate changing force, the loss from soils is maximum a few percent

[4] Department for Environment, Food and Rural Affairs

of applied nitrogen [23] and considered small compared to the overall flow of nitrogen through agriculture. It is therefore beyond the scope of this thesis to assess N_2O mitigation options in agriculture. The characteristic of the losses (non-point) and that N_2O is not useful in agricultural applications further motivates this. However, recent studies show that high NO_3^- levels in water streams can be a source of N_2O emissions [24]. Reduced system losses from agriculture could therefore also have climate benefits beyond the directly decreased eutrophication potential.

Eutrophication of aquatic systems is a serious environmental problem, where agriculture is responsible for about 60% of the nitrate load causing it in the UK [25]. There is a non-linear relationship between applied nitrogen and leaching to water and there is no single parameter to predict the leaching [26]. But for the UK it seems that most nitrate loss is caused by high rainfall [27, 28, 29] that drains the soil of plant-available highly water-soluble nitrate. Other measures than timing in application may be necessary to mitigate the leaching, and this forms a critical part of the research in this thesis.

2.2.5 Policies for improved management

The Common Agricultural Policy (CAP) in the European Union (EU) is focused on rewarding good behaviour, e.g adapting to environmentally friendly practices and provide other environmental services than just food production [30]. This is part of a larger legislative and regulatory framework in the EU to protect the environment. For example, the Nitrates Directive in the EU is developed to regulate the agricultural industry into practices that reduce the nitrate emissions to surface and ground water [31]. It is implemented through codes of good practice, on a voluntary or compulsory basis. The concrete implementation of governmental strategies is often carried out through manuals and guides. The Fertiliser Manual [32] for example is supposed to guide farmers and land managers to best management practices for efficient nitrogen use. The implementation of Nitrate Vulnerable Zones (NVZ) are supposed to reduce the load of nitrate to water systems. NVZs are areas on agricultural land where fertiliser and manure application, crop cultivation or livestock grazing is regulated due to the risk of nitrate leaching, for example on steep land or near water courses and in certain soil types. The situation has improved lately, but results show that nitrate levels are still above threshold levels on many sites in the UK [25, 33].

Best Management Practice (BMP) manuals [3, 32] also encourage farmers to use cropping practices that improve soil and hinder leaching. Cover crops, also called catch crops, grown on adjacent fields or on cash crop fields during off-season, absorb excess fertiliser and hinder erosion. Cover crops can also form buffer strips[5] between arable land and water courses. These crops are not always harvested but can be ploughed into the soil to provide an organic source of nitrogen and organic material, then called green manure. Legumes can be grown as cover crops in nitrogen poor soils, thereby fixing new nitrogen that is available to the following cash crop, and reducing the fertiliser need.

[5] Also called riparian zones if they are in constant vegetation

Other BMP to minimise nitrogen losses include proper storage of manure and fertilisers, ensuring incorporation or deep application of especially ammonia-containing fertiliser/manure [8], and soil testing to match the nitrogen application with the supply from the soil to meet crop demand [3, 8]. Planting date of crops is also important [34], since bare land is more prone to leaching.

2.2.6 The linear flow of nitrogen

Increased nitrogen use efficiency must be a priority the coming decades if the global losses of reactive nitrogen shall not increase further when agricultural production expands to meet the demand for food [35, 36]. This is important even in a relatively N-efficient agriculture as in the UK. Much focus in research is on nitrogen use efficiency on field and farm level. All these practices will most certainly improve the on-farm nitrogen economy, but from a systems perspective there is a risk of suboptimisation. Despite reduced losses after introduction of NVZs, nitrate concentrations in water streams in the UK remain above the set threshold of 30 mgL^{-1} in several places [25]. However, if this threshold is set from natural background levels was not identified during the research in this thesis, and it is therefore suggested that eutrophication could remain as a problem if threshold levels are set out of convenience rather than from environmental constraints.

Wastewater treatment plants are responsible for 32% of the nitrate load to water systems in the UK [25]. This nitrogen originates in the food consumed by humans and shall be seen as a loss from the socio-agricultural system, since the food consumed is produced by agriculture. Some efforts are made on denitrification of nitrate into N_2 in the treatment plants. To instead recover and recycle this nitrogen might not be easy or always feasible, but bioenergy crops can be irrigation-fertilised with wastewater without concerns for infection of food crops, see further Section 2.3.

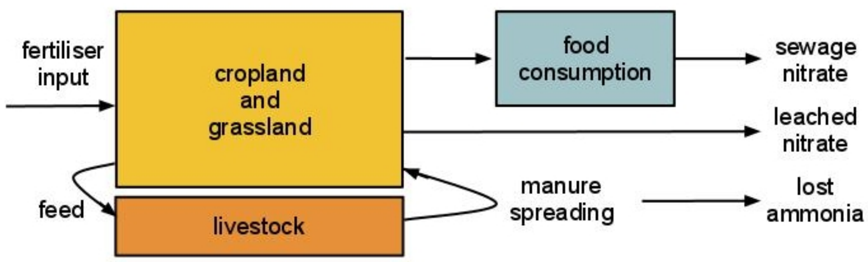

Figure 2: Simplification of the nitrogen flows through the socio-agricultural system in the UK today.

As is shown in Figure 2, apart from some recycling of manure (with losses of ammonia), the flow of nitrogen through agriculture is linear considering that nitrogen ends up in aquatic ecosystems after leaching from cropland and being discharged from sewage treatment plants. Recycling of nitrogen is, therefore as important as trying to minimise the losses.

2.3 Cellulosic bioenergy: part of the remedy

2.3.1 Bioenergy important anew

Bioenergy from biomass is a traditional source of energy somewhat forgotten in the industrialised world under the fossil energy regime. Due to the recent discussion on climate change and energy security, bioenergy has again come in question, especially in the form of biofuels, and is seen as an option to mitigate climate impact from the energy and transportation sector and reduce the dependence on fossil resources. The future global biomass potential has been estimated in several studies [37, 38, 39] and the potential lies between 200-500 EJ per year in 2050 [40], which is about one third of total projected energy demand at that time. This potential is, however not without concerns for biodiversity, water use and effects on food production.

Bioenergy is part of renewable energy together with solar, wind, water and wave power. The EU is implementing a goal of 20% renewable energy in the energy sector in 2020 [41]. Liquid biofuels are currently more mature than other technologies such as hydrogen, since they partly can rely on the fuel infrastructure for the internal combustion engine. The Biomass Strategy in the UK builds on the governmental strategy with goals including, among others, to "realise a major expansion in the supply and use of biomass in the UK" and "contribute to overall environmental benefits and the health of ecosystems through the achievement of multiple benefits from land use" [42]. How this in practice will be implemented or what the effects will be on agriculture seem not sufficiently researched.

2.3.2 1st and 2nd generation biofuels

1st generation biofuels refer to the currently used technology of converting starch (sugars) into ethanol by fermentation, or plant oils into diesel by chemical conversion. The feedstocks in Europe for this technology is annual food crops, such as wheat, maize or rapeseed[6]. Since the feedstocks are food crops they are cultivated on current agricultural area. This has raised concern about competition for land [43] and possibly increased food prices. The crops used as biofuel feedstocks require high fertiliser input and intensive management with the same risks of leaching with subsequent environmental impact as for food crop production, as described in Section 2.2. 1st generation biofuels face challenges concerning energy use and emissions from cultivation, conversion efficiencies and, as mentioned, competition with food production over feedstocks and agricultural land [44]. The environmental and climate implications of 1st generation biofuels vary for every production system, and the benefits compared to a fossil system are therefore not obvious. Instead it has been discussed whether the general policy promotion of all 1st generation biofuels really is anchored in evidence of environmental benefits of these systems [45].

2nd generation technology builds on conversion of (perennial) cellulosic crops (also called lignocellulosic crops or woody species) or herbaceous grasses. Perennial crops are plants that have root systems surviving several years, where har-

[6] In the tropical regions of the world ethanol is produced from sugarcane, which is a semi-perennial with different environmental implications than the mentioned food crops

vest is possible annually or after several years. Grasses can be perennial or annual, and have lignocellulosic structures (but are not woody), for example switchgrass or miscanthus. Eucalyptus and poplar are examples of single-stem lignocellulosic perennials, that are harvested after several years. Willow is also harvested with several years in between, but have multiple stems. This type of cellulosic crop is often called Short Rotation Coppice (SRC). The benefits of cellulosic plants in agriculture are described in Section 2.3.4.

The 2nd generation conversion technology into fuels is more complicated than 1st generation. One route is biochemical (enzymatic) breakdown of the lignocellulosic structures into sugars, with further fermentation into ethanol. The second, and more flexible, route is gasification of biomass material into syngas (consisting of CO and H_2). The syngas can then be converted through the Fischer-Tropsch process into ethanol, diesel, and other fuels such as aviation fuel [46]. Second generation technology is still not fully commercial [43], but have the potential to be this decade if it can partly rely on the already installed infrastructure and policies for 1st generation fuels [46]. Cellulosic production systems and 2nd generation conversion technologies generally have better environmental and climate performance than 1st generation processes and crops [44]. Recycling of nutrients back to land after biofuel production would save nitrogen input and increase the environmental performance of the system [47, 48].

2.3.3 Biomass for heat and power

Biomass is traditionally used as heating and cooking fuel. In modern times, biomass residues from agriculture and forestry sometimes serve as fuel in combined heat and power generation (CHP), or as wood pellets. One way to make cellulosic bioenergy production cost-competitive could be to co-fire biomass with coal [49] since co-firing does not require costly investment in special technology, and at the same time save CO_2 emissions from replaced fossil fuels. This could especially be an option for the UK, that relies on coal energy to a large extent. However, it should be pointed out that co-firing with coal will imply that nitrogen in biomass and N_2 from air are oxidised (i.e.unintentional fixation) and lost as NO_x emissions that deposit as nitrates with rain and cause eutrophication and acidification of terrestrial and aquatic ecosystems.

2.3.4 Function of cellulosic crops in agriculture

For biofuels, perennial cellulosic crops perform better than annual (food) crops on criteria regarding land use, energy use and nitrogen use efficiency [50, 51, 52]. This is because (perennial) cellulosic crops put less stress on soil, require less fertiliser input and have longer growing seasons (more efficient use of total annual solar radiation) [53]. Perennials can also benefit local biodiversity since there is less disturbances in the soil and vegetation and reduced need for pesticides compared to cropland for annual crops [54, 55, 56]. A substitution from a food crop to a cellulosic perennial for bioenergy production reduces nitrogen load to nearby watersheds [57], due to the above mentioned characteristics. Cellulosic crops integrated into the agricultural landscape could therefore mitigate rather than increase the nitrogen-related environmental problems.

Crops can be classified into the main photosynthetic types C3 or C4[7]. C4 crops (for example switchgrass) use CO_2, water and solar radiation more efficiently than C3 crops (for example willow) [53, 56], since they have evolved and adapted to different climate conditions. C3 crops can therefore still have a good system performance, for example as water treatment systems. Willow has good remediation characteristics, and as a water demanding C3 crop it is suitable to irrigate with landfill leachate, sewage sludge and nitrate-rich water from wastewater treatment plants [58, 59, 60]. The loads of nitrate, heavy metals and chloride can be high without damage to the plant. This is an example of a multifunctional system since it gains both bioenergy and cleans wastewater cost-efficiently. Experience from a three-year study in central Sweden by Aronsson *et al.* [58] report no negative impact on willow from high load of landfill leachate, but some impact on groundwater quality. Treatment of landfill leachate on willow plantations has been evaluated in the UK [61], although it has not yet been implemented on a larger scale. Willow can also absorb water in drainage from intensively cultivated cropland [60], which is an option for nitrate leaching interception that will be used in this study. Figure 3 shows a willow plantation from a study in Enköping, Sweden, irrigated with nitrate-rich wastewater from a sewage treatment plant [60].

Figure 3: View from above of a willow plantation irrigated with nitrate-rich wastewater from treatment works, from studies in Enköping, Sweden [60]. Photo: Pär Aronsson, Swedish University of Agricultural Sciences.

Alleycropping is an other type of multifunctional system and means intercepting a monoculture with alleys of perennial crops. This has been proven to be effi-

[7]Meaning how CO_2 is converted to sugar in the plants; if the carbon atom is first incorporated into a 3-carbon or 4-carbon compound

cient in maintaining soil fertility by hindering nutrient loss, preventing erosion, sustaining yields, increasing water use efficiency, restoring biodiversity, and be an option for carbon sequestration and a source of bioenergy [62]. Integration of perennials into the landscape creates a more varied environment (habitats) for animals and can have a cultural value for humans. Overall it seems that alleys and buffer strips of perennial cellulosic crops could improve the nitrogen situation if integrated into agricultural cropland.

Cattle livestock that are not grazing are often fed forage, which are herbaceous grasses and cellulosic perennial crops. Of the forages produced for livestock today, many are also suitable for bioenergy production, which could make implementation easier since farmers are already familiar with cultivating them [63]. However, much livestock in the UK is also grazing on grassland [15], where yields of grass does not reach the same amount as harvested forage and losses of nitrogen from deposited manure is substantial. A more land-efficient forage and grazing system could open up for bioenergy production.

2.3.5 Bioenergy from anaerobic digestion of waste

Another type of bioenergy is biogas (also called biomethane) produced from anaerobic digestion (AD) of waste. Farm residues, like straw and manure is cellulose-rich and suitable for this process, which allows for nutrient recycling after the digestion. Normally, manure in itself can be used as fertiliser, but the high content of volatile NH_3 results in large losses. Anaerobic digestion is therefore a more efficient way to manage and treat manure, since the volatile ammonia is stabilised in the digestate as non-volatile nitrate. Decentralised on-farm digestion for gas production is not so widespread today, but the technology has become more in focus, along with general popularity as waste handling [42].

2.4 Industrial Ecology: tying the parts together

This theory chapter has outlined the nitrogen issue in society, with a focus on how the problem is caused by the anthropogenic influences on the nitrogen cycle through fixation of reactive nitrogen and use of fertilisers and manure in agriculture. Figure 4 provides a perspective on how the socio-agricultural system is part of an open interaction with the nitrogen cycle. Fixation of nitrogen into reactive compounds through the Haber-Bosch process, together with poor nitrogen management, causes the losses from the socio-agricultural system. The environmental impacts, such as eutrophication and acidification of soils and aquatic systems, resulting from a poorly controlled nitrogen flow were factors initiating this project. Anthropogenic denitrification could be a way to deal with excess reactive nitrogen in the socio-agricultural system, as for example is done to some extent in wastewater treatment works or wetland restoration, as described below. This thesis, however focuses on minimising the losses along the dashed arrow in Figure 4 and increase the internal recirculation of reactive nitrogen, as a way to reduce the environmental impacts and decrease the need for new fixation.

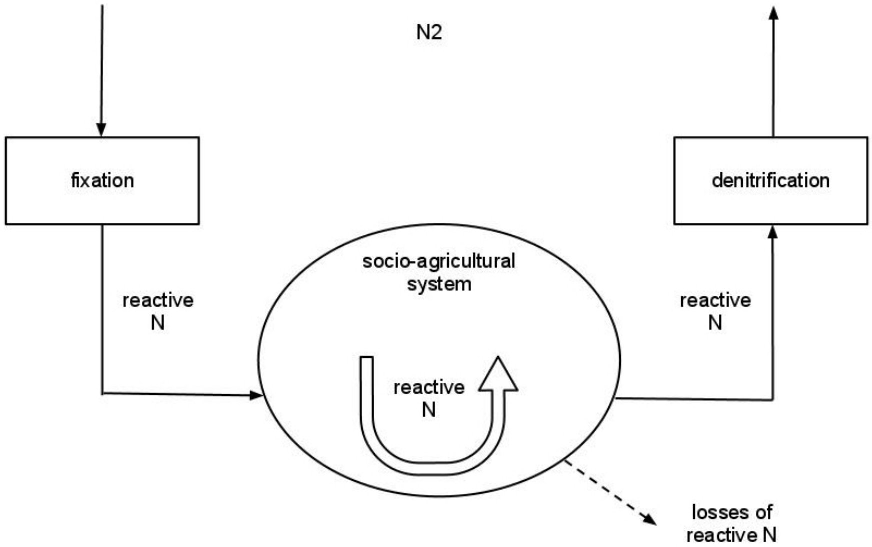

Figure 4: Perspective on the socio-agricultural system and the nitrogen problem described in the thesis.

Industrial Ecology (IE) is a relatively new scientific field that builds on the idea that industrial systems should resemble ecological systems in nature in terms of resource efficiency and nutrient recycling [64]. The theory is often applied to flow management of scarce resources such as metals (rare earth) or connecting industrial systems producing goods and energy. The concept that resources are extracted from the ecosphere, used in the technosphere, and then emitted back to the ecosphere [65], is illustrated as:

$$extraction \longrightarrow \underset{use}{\bigtriangledown} \longrightarrow emissions$$

However, these principles can also be applied to biologically oriented systems such as nitrogen in agriculture. Modern agriculture in developed countries (e.g. in the UK) resembles rather an industrial system than subsistence farming. As has been shown in Section 2.2, the flow of nitrogen in industrialised agriculture can be viewed as being linear, with large losses of nitrogen to the environment. This loss causes substantial environmental impact and demands costly fixation of new nitrogen into fertilisers. In some regions efforts are made to restore wetlands adjacent to arable land. Their function is to denitrify leaching nitrate from agricultural land into harmless N_2 gas. While this function is reducing the load of nitrate to water systems, it could, from an industrial systems perspective, be seen as a loss of valuable nitrogen. The same could hold for denitrification of nitrate in wastewater treatment works. The nitrate is a valuable nutrient that originally was fixed into fertilisers with great effort and energy. Therefore, there is a call for thinking more about recycling of nitrogen than "end-of-pipe" fixes to potential emissions. The concept of resource flows applied to the nitrogen flow in the UK today is illustrated in Figure 5.

Figure 5: Conceptual nitrogen flow through agriculture in the UK today.

Reducing the flows of substances per unit service or product is in IE called "dematerialisation" [65]. It can in this case either be a minimisation or a closing of the flow. This thesis focuses on closing the flow, i.e. recycling of reactive nitrogen from different parts of the socio-agricultural system back to productive land, with minimised input and losses. This principle is illustrated as:

$$\textit{necessary input} \longrightarrow \underset{\textit{recycling}}{\circlearrowleft} \longrightarrow \textit{unavoidable losses}$$

A way to follow and monitor system changes, that is common in IE, is by environmental indicators [64]. This thesis will adopt an indicator based on physical amounts to be used in the sensitivity analysis, see Section 5, to compare the nitrogen flow performance of the analysed scenarios, i.e. the performance of the model and those flows included. The "flow ratio" is a measure of how large the recycling is within the system compared to the necessary chemical fertiliser input (i.e. fixation by legumes is not included):

$$\frac{\textit{recycling}}{\textit{fertiliser input}} = \textit{flow ratio}$$

It has been proposed that nitrogen is for food what carbon is for energy [66], i.e. nitrogen fertilisers are for agriculture what fossil fuels currently are for the energy system. However, while decarbonisation of the energy system is physically possible, a nitrogen-free agriculture is biologically impossible. What is possible, though, is a more closed flow with increased recirculation of the reactive nitrogen already fixed to the socio-agricultural system. Such a system, following the principles described above, will be developed in Section 3.

3 Building an alternative agricultural system

This section describes a model of an alternative agricultural system, that maintains the food and livestock production output in the UK at today's levels, but is modified for increased nitrogen recirculation. This scenario is described as "Basic", and will be used in comparison with scenarios in the sensitivity analysis in Section 5. For further details about assumptions, data and calculations, see Appendix A. The agricultural land use areas in the UK has changed little over the last decade [15] and therefore data for 2010 is assumed to be a robust representation of the land areas incorporated into the model.

3.1 Starting point

Based on the previous section the current agricultural system in the UK will be regarded as "high input, moderately efficient". UK has a total utilised agricultural area (UAA) of 17.233 Mha [67]. This thesis models 97.7%[8] of that, including all grassland and arable cropland under tillage. Table 1 shows the categories and areas as well as their function today. The land areas are the starting point for the modelling but their function will be changed. Details of arable land areas and crops can be viewed in Table 7 in Appendix A.1.

Table 1: Agricultural land classes and areas included in the model and their function in the UK today.

Land class	**Area** (Mha)	**Function today**
Arable land	4.390	Food/feed crops
Temporary grassland	1.232	Forage production
Permanent grassland	5.925	Grazing/forage production
Sole + rough grazing land	5.283	Grazing
Total area modelled	**16.83**	
% of UAA	*97.7%*	

3.2 Arable crops and nitrogen leaching interception

The crops on arable land will be cultivated in almost the same rotational regime as today (for example rotations of wheat, barley, oilseed rape, sugarbeet etc.). The temporary grassland area of 1.232 Mha (see Table 1) in the UK is today part of these crop rotations and therefore adjacent to arable fields. However, in the model this temporary grassland will be taken out of the rotations and instead used for cultivation of a perennial cellulosic crop. This cellulosic perennial will intercept and absorb some of the nitrogen leaching from cropland. A total area of 1.232 Mha is cultivated with a perennial crop, but rearranged together with the 4.390 Mha cropland so that the perennial areas are *integrated* into the food production areas, to catch the leaching nitrogen. The perennial forms alleys inside the arable crops fields. Near water streams the perennial should be arranged in buffer strips to provide a broad filtration area between water courses and cropland. An example arrangement can be seen in Figure 6. The

[8]Excluded areas are uncropped arable land, land for outdoor pigs, and horticultural crop areas (fruit and vegetables, hardy nursery stock, glasshouse), totalling 0.393717 Mha

integration should also be arranged to provide wind barriers to protect from soil erosion, and to increase local biodiversity and animal habitats.

The chosen perennial for the integration is willow, since it is cultivatable in the soil and climate in the UK [32]. As described in Section 2.3, willow is suitable for leaching interception from cropland. It can withstand a load of at least 200 kg_N per hectare annually without damage to the plant [68], but leaching may occur since uptake is lower than this. Nitrogen demand for willow ranges between 30-100 kg_N [32, 60, 69], depending on yield. However, calculations are based on an uptake of 100 kg_N per hectare annually, since load from cropland will be high and willow can absorb high nitrate loads [60].

Due to crop rotations, nitrogen application rates vary between years for the same field, and therefore also the leaching will differ from year to year. Cultivation cycles for willow should start so that willow nitrogen demand is high when leaching load is high. This occurs after harvest, in the beginning of a 3-year cycle [70], but not during initial planting year when root systems are not fully developed [68]. Even if harvest only occurs every three years, an average annual harvest is calculated in the model. Since willow translocates the nitrogen in the above-ground biomass to the root system during winter [70], willow should be harvested during another season to optimise the benefit of leaching interception and maximise nitrate absorption.

Since the perennial area will be smaller than the crop area, the load to the perennial per area unit will be higher than the leaching from cropland per area unit. This is here called the field ratio, see illustration in Figure 6. 1.232 Mha perennial over 4.390 Mha cropland, gives a field ratio of 28% on a systems level, i.e. the load per area unit to the perennial is several times higher ($\frac{1}{0.28} = 3.57$) than the leaching per cropland area unit. This ratio is regarded as reasonable for providing adequate leaching interception and nitrate absorption.

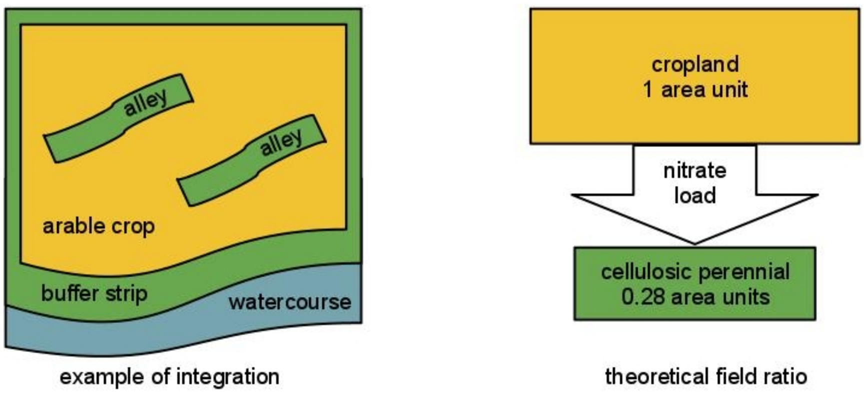

Figure 6: Example of leaching interception arrangement and illustration of the theoretical field ratio between cropland and intercepting zones per area unit.

Wheat and barley are the most important food crops in the UK [67]. Uptake efficiency of ammonium-nitrate fertiliser in winter wheat and winter barley is estimated to lie between 55-70% depending on soil type [32]. This model uses an average uptake efficiency of 60% [71] for all arable crops in the UK, i.e. leaching of nitrogen is 40% of fertiliser input[9]. The ultimately lost nitrogen after willow interception is calculated according to the following principle:

$$\left(\frac{application\ rate \times leaching}{field\ ratio} - willow\ uptake\right) \times field\ ratio \times crop\ area = final\ loss$$

Detailed application rate, leaching and final loss per crop is available in Appendix A. Results for total fertiliser input and ultimately lost nitrogen from cropland is shown in Tables 4 and 5 in Section 4.

3.3 Livestock, grazing and forage production

3.3.1 Livestock units

To facilitate calculations and comparison, livestock numbers have been converted into Livestock Standard Units (LSU)[10] where each livestock category has a conversion factor. Livestock categories[11], resulting LSU and how each category will be fed in model is presented in Table 2. Livestock numbers have declined over the last decade [15], and the livestock factors from [72, 73, 74, 75] were adapted to match this trend. Grazing and forage production areas for concerned LSU categories will be allocated.

Table 2: Livestock units in model, numbers rounded from Appendix A.2.

Category	*M LSU*	**How fed in model**
Ruminants		
Cattle	8.1	Forage, protein feedstuffs
Sheep and goats	3.1	Grazing
Non-ruminants		
Pigs	1.0	Feedstuffs
Poultry	1.0	Feedstuffs
Horses	0.25	Feedstuffs
Total LSU	**13.45**	

3.3.2 Pigs, poultry and horses

Pigs, poultry and horses are non-ruminants. These livestock categories are fed feedstuffs, i.e. feed produced from cereals and other grains cultivated on food production areas, or imported. The separate feedstuffs flows are not quantified in the model, but seen as part of production from arable land. Important nitrogen flows from this section is nitrogen in horse manure that is assumed to be lost (not collected and recycled), and manure from pigs and poultry that *is* collected and recycled, see further Section 3.5 and Figure 7 in Section 4.

[9] N2O losses are not assessed in this model, as justified in Section 2.2.
[10] 1 LSU = one cow with certain milkproduction, see detailed definition in Appendix A.2
[11] Some categories were excluded, see Appendix A.2

3.3.3 Sheep and goats

The land class "Sole + rough grazing land" in Table 1 implies land that is poorly suited for agriculture, called Less Favourable Land (LFA). This includes mountains, hills, heathland and moorland. In the model, grazing ruminant livestock, i.e. sheep and goats, will be allocated to this area (as is the case today) since these animal categories are not suited for indoor keeping. The LFA land type can support a stocking density[12] of 0.16-1.0 LSU per hectare [76, 77, 78, 79]. In the model, a stocking density of 0.60 LSU per hectare is chosen to assure no overgrazing with risk of erosion, but to sustain the 3 million LSU of sheep and goats on the 5.283 Mha land.

This system of livestock grazing is seen as separate in the model and lies outside the quantified system boundaries, see Figure 7 in Section 4. The manure excreted by the animals is assumed to fertilise the grass, with some additional input from atmospheric nitrogen deposition, which is high in the uplands due to rainfall patterns [75]. The only nitrogen flow from this subsystem is export of nitrogen in meat but that will not be quantified. No significant losses from this part of the model are assumed.

3.3.4 Cattle

In this model, cattle will not be grazing (as is often the case in the UK) but kept in confined spaces and fed forage feed, to allow for efficient manure collection. Total Digestible Nutrients (TDN) is a feed measure that reflects the intake of energy, proteins and fibres for 1 LSU[13]. 1 LSU corresponds to an annual intake of $\sim$ 2.44 tonnes TDN. However, protein intake, here expressed as crude protein (CP), must be about 25% of the diet on a TDN basis [80]. A large part of the consumed feedstuffs in the UK are fed to cattle, of which several have a protein content above 25% [81]. This is because the forage that cattle are fed (or the grass they graze) has to be complemented with protein rich feed concentrates, which are often made from imported soybean or maize. In the model, these extra feed concentrates are assumed to provide 5% of the protein need[14]. The forage feed therefore needs to provide 20% proteins on a TDN basis.

The two forage crops chosen for the modelling are switchgrass and alfalfa, since they can be fed directly to cattle without processing. Switchgrass is a perennial grass, with yields of up to 15.4 tonnes of dry matter (DM) per hectare annually in the UK [82, 83], and CP content per dry matter of 7.5% [84, 85, 86, 87]. A moderate annual yield of 10 t_{DM} per hectare is chosen for the model. Alfalfa is a perennial herb. It is also a legume and fix its own needed nitrogen. Yields vary between 8-22 [88, 80], and 10 t_{DM} annually per hectare is chosen to reflect the cooler climate in the UK. Protein content per dry matter vary between 14-24% [88, 80] but for the model 22% is chosen, as in high quality forage. The protein content of switchgrass is low and therefore supplemented by the higher protein content of alfalfa. To supply a protein content of 20%, alfalfa will be 32% and switchgrass 68% of the energy intake on a TDN basis. Cattle shall not be fed

[12] Number of animals per unit area

[13] For definitions and conversions, see Appendix A.2

[14] This assumption may cause an overestimation of total energy intake since concentrates also contains carbohydrates

too much alfalfa to avoid bloating [88], and 32% of the diet is assumed to be acceptable. Land area results are shown in Table 3 in Section 4.

Nitrogen need for switchgrass ranges between 56-200 kg_N per hectare annually [83, 89, 90]. 120 kg_N is used in the model[15]. Biological fixation of nitrogen by alfalfa, that is relevant for the model, is the same amount as exported in proteins with harvest. Other fixed nitrogen may be important for soil and roots, but that inflow is not quantified. Switchgrass and alfalfa nitrogen input is available in Table 4. Other flows relevant from this section is nitrogen in cattle manure that is collected, see further Section 3.5 and Figure 7 in Section 4.

3.4 Bioenergy production with nitrogen recycling

Switchgrass and alfalfa forage production is not using all available (=permanent) grassland. The remaining area opens up for bioenergy production. Bioenergy will be produced from willow. Willow is also, as previously described, produced on the grassland ("temporary grassland") integrated with crop fields (integrated-willow). It is fertilised by absorbing leached nitrogen from cropland. The willow on remaining grassland (bioenergy-willow), however, needs to be fertilised. In the Basic scenario it is assumed that willow production is feasible on all the remaining grassland. Yield of willow varies in the reported literature between 4-30 t_{DM} per hectare annually [32, 60, 70, 91, 92]. For this model a moderate yield of 12 t_{DM} is chosen to reflect climatic conditions.

Since this thesis aims at closing the flow of nitrogen, a suitable end route for the bioenergy is chosen to allow for recycling of nitrogen. Biochemical breakdown of cellulose and fermentation to produce ethanol is such an end route (and one of the 2nd generation technologies). This will provide liquid biofuel for the transport sector. It would, however, also be possible to gasify the biomass to syngas with further conversion into fuels. Gasification also allows for recovery of nitrogen (as ammonia), so ethanol production is chosen in the model just as an example. General conversion efficiency yield for current cellulose ethanol technology is 300 litres of ethanol per t_{DM} [47, 93].

The solid residue that remains after the fermentation contains a lot of nutrients. If the residue is gasified, nitrogen in the form of ammonia can be recovered in an absorption column and the ammonia used as fertiliser. This process can recover 82% of the nitrogen in the biomass [47]. In the model a 10% loss when handling and spreading the recovered ammonia is assumed, resulting in a total recovery potential of 73.8%. The relevant nitrogen flows from this sections is fertilisation input to bioenergy-willow, recycled nitrogen and lost nitrogen from the process. Results are presented in Tables 4 and 5 in Section 4.

3.5 Manure digestion and nitrogen recycling

In this model, all cattle, pigs and poultry will be confined to spaces where quick collection of manure is possible. 1 LSU excretes about 53 kg manure per day [94], which is around 20 tonnes per year [94, 95]. The manure will be anaerobically digested for nitrogen recycling and biogas production. Decentralised on-farm

[15] Adjusted to suit assumed crude protein content in harvest extraction, see Appendix A.2.3

digestion for gas production is assumed to be fully implemented in the model. Preferably the manure shall be mixed with straw or other cellulosic material to hinder ammonia inhibition in the digestion process. Methane potential of manure on a weight basis from different livestock is similar [96], so one yield level will be used. Methane production potential, on a Total Solids (TS) basis, ranges from 150 to over 190 m^3 methane per t_{TS} [97, 98], therefore a value of 175 m^3 methane per t_{TS} is chosen for the model, to include losses during storage and handling of the produced methane gas.

Anaerobic digestion stabilises the nitrogen in manure, which remains in the digestate [99]. 75% of the nitrogen intake (proteins) in livestock is excreted [94], which is why recycling of manure is important for the flow. The nitrogen output in manure is annually $\sim 85kg_N$ per LSU [94]. This nitrogen is found in ammonia and organic compounds in the digestate, which is spreadable as organic manure on crop fields. 15% of the nitrogen is assumed lost as ammonia through handling, storage and application, based on various sources [19, 20, 21]. Relevant flows from this section are recycled and lost nitrogen, presented in Tables 4 and 5 in Section 4.

3.6 The "black box" of food consumption

The flows of nitrogen in food and feed products were not possible to track due to lack of separate data, and complexity regarding import and export into and out from the UK. Therefore food consumption and feed production were put together into a "black box", that also contains the flows of nitrogen in exported and imported products. The feedstuffs production therefore lies outside the quantified system boundaries in the model system, see Figure 7 in Section 4. Some estimations of the flows to and from the "black box" were made, and there is a net *outflow* of nitrogen over the system boundary into the "black box", mainly due to nitrogen in meat products, see further Appendix A.5. Since the UK is not self-sufficient in food production [15] there is an inflow of nitrogen to the "black box" in imported food products - which end up in wastewater treatment works. This explains the high nitrate load from wastewater treatment in the UK, further presented in Section 3.8.

3.7 Other nitrogen flows not included

Some nitrogen flows are *not* included in the modelling. Those are: import/export of food/feed and food consumption (as described above), atmospheric deposition of NO_x from anthropogenic combustion (unintentional fixation not included in the scope), deposition of volatilised NH_3 and influence on yields (calculated as loss only), and N_2O emissions from soil or fertiliser production. The possible influence an inclusion of these could have on the model results is analysed in the sensitivity analysis, see Section 5.

3.8 Options for additional nitrogen flow improvement

The model described in this chapter is an attempt to create a closer flow of reactive nitrogen in the socio-agricultural system. Naturally, all systems contain losses to some extent, and a need for newly-fixed chemical fertiliser is therefore realistic. The model flows of nitrogen will be presented in Section 4, and these will represent a more closed flow than today's agriculture, but with a resulting chemical fertiliser need. However, there are additional alternatives, not fully quantified in this model, to decrease the need for chemical fertiliser produced with fossil energy.

As has been described, nitrogen in consumed food end up in wastewater treatment works. Due to lack of recent and separate data, no estimate of the national load of nitrogen from sewage in the UK was available, and therefore this loss of nitrogen to sewage systems lies outside the quantified system boundary. However, the nitrogen load to water systems from wastewater treatment works was 175 000 tonnes in 2001, only from England and Wales [33]. It is assumed in this modelling that a recent figure, and for the whole of the UK, would be at least at this level. The wastewater could fertilise bioenergy production through irrigation, both since willow is resilient to other substances such as heavy metals and chloride but also for health issues regarding wastewater on food crops. This is **Alternative 1: nitrate-rich wastewater from sewage treatment**, and can reduce the remaining need for chemical fertiliser in the model.

If treated wastewater is not feasible to use, the resulting nitrogen need will have to come from chemical fertilisers. Fertilisers are produced through fixation of N_2 from the atmosphere into NH_3, with H_2 produced from natural gas. Natural gas consists of about 87% methane, and therefore methane in biogas from digestion of manure can be used [100]. This will result in CO_2 emissions from the fertiliser production, but the carbon originates in organic, renewable material. This provides **Alternative 2: fertiliser produced with biogas**. The flow will be less closed than with Alt 1, but provides a renewable way to produce needed fertilisers.

The identified alternatives for an additional improvement of a near-closed flow are included in Figure 7 in Section 4.

4 A system with increased nitrogen recycling

A system flowchart is presented in Figure 7, which shows all the nitrogen flows, plus bioenergy output, and the production arrangement in the "Basic" model scenario. The green and blue modules are the interventions assessed in the model. The alternatives for additional system improvement is showed as Alt 1 and Alt 2 in the flowchart.

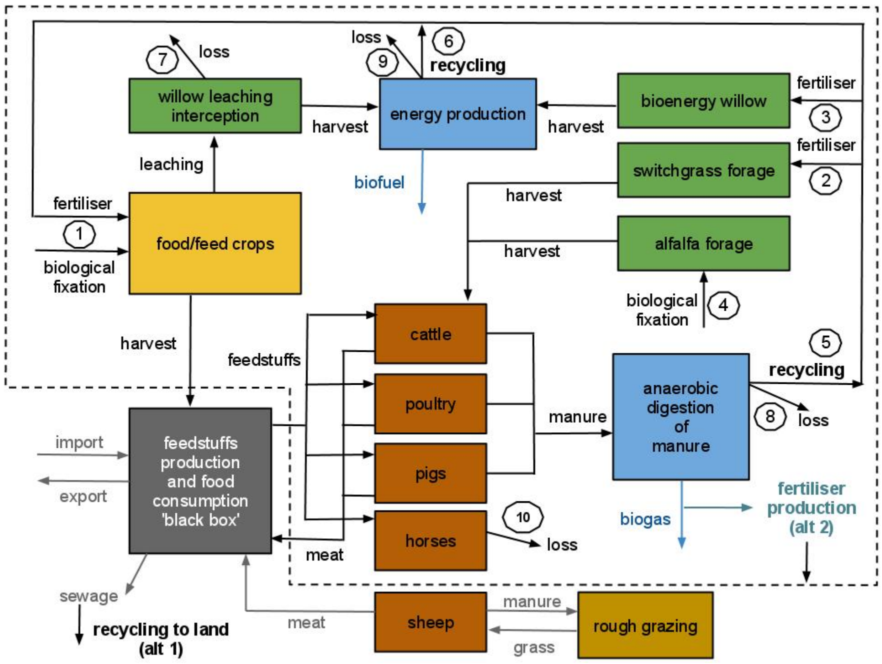

Figure 7: System flowchart and general production arrangement. Black arrows = quantified nitrogen flows, blue arrows = energy produced, grey arrows = nitrogen flows not quantified and dashed line = system boundary for quantified system. Actual land areas can be viewed in Table 3. The numbered flows correspond to the quantities presented in Tables 4 and 5.

Table 3 shows the corresponding areas and their function. Quantities of the numbered flows in Figure 7 are shown in Tables 4 and 5. "Arable crops" include the nitrogen that is leached from cropland and absorbed by the perennial. The "Nitrogen input to land" is the total fertiliser input and biological fixation in the model, then discounted with recycling and biological fixation to result in the "newly fixed" fertiliser need. Corresponding, more detailed Tables 9 and 10 are available in Appendix A.7.

Table 3: Land areas and their function, corresponding to Figure 7.

Land class	**Area** (Mha)	**Function in model**
Arable land	4.390	Food & feed crops
Temporary grassland (willow)	1.232	Leaching interception and bioenergy production
Sole + rough grazing land	5.283	Grazing
Permanent grassland:		
- Switchgrass	2.433	Forage production
- Alfalfa	0.954	Forage production
- Willow	2.538	Bioenergy production
Total area modelled	**16.83**	

Table 4: Quantified flows of nitrogen in the model system, with reference to flow number in Figure 7.

Activity	**Quantity** (t_N/yr)	**Number**
Nitrogen input to land		
Arable crops	+ 697 209	1
- of which, peas and beans fixation	(20 800)	
Switchgrass	+ 291 978	2
Bioenergy (willow)	+ 253 763	3
Alfalfa fixation	+ 335 870	4
Recycling		
Manure digestion	- 728 974	5
Bioenergy production	- 278 202	6
Net inflow to system	**571 648**	
Biological fixation		
Peas and beans	- 20 800	
Alfalfa	- 335 870	
Fertiliser input need	**214 978**	

Table 5: Quantified **losses** of nitrogen from the model system, with reference to flow number in Figure 7.

Activity	**Quantity** (t_N/yr)	**Number**
Final loss from arable land	156 622	7
Manure digestion	128 643	8
Bioenergy production	98 765	9
Horse manure	21 148	10
Total	**405 178**	

The main results from the modelling are:

- The leaching interception module reduces the losses of nitrogen substantially. Table 5 shows that the final loss from cropland to water systems after leaching interception is 156 622 tonnes for the whole of UK, compared to leaching from agricultural land that was 330 000 tonnes in *only* England and Wales in 2001 [33].

- The final loss from cropland in the model is still significant compared to other model losses. Wheat production is responsible for 58% of this leaching. The high fertiliser input results in large leaching and therefore a very high load to willow, that willow cannot absorb because of the field ratio.

- When recycling and biological fixation are discounted from the inflow to land, the remaining fertiliser need is about 0.2 million tonnes of nitrogen. This can be compared to today's fertiliser input of 1.1 million tonnes of nitrogen. The model provides a substantial improvement/reduction of the fertiliser need.

- The remaining fertiliser need of 214 978 tonnes of nitrogen for the whole of the UK could probably be almost fully covered by recycling of nitrate-rich wastewater from sewage, that was 175 000 tonnes in 2001, *only* from England and Wales [33]. This was described as Alternative 1, and could contribute to reaching an almost fully closed flow *in the model*.

- The biogas from anaerobic digestion can supply 2.4% of the gas consumption in the UK in 2009. To produce the 0.2 million tonnes of fertiliser need in Table 4, only 8% of the methane gas from digested manure is required, the remaining 92% could be fed to the gas grid. This was described as Alternative 2; a way to produce the needed fertiliser that recycling cannot cover in the model, but with renewable energy.

- There is a substantial production of bioenergy (willow) from the leaching interception and on the remaining permanent grassland. The produced biofuel can supply 17% of the transport fuel consumed in the UK in 2009. For comparison: in 2009 renewables were 2.5% of the transport fuel in the UK [101]. The model shows a potential for a large increase in biofuel production.

- The "Net inflow to system" in Table 4 shall be compared to "Total" loss in Table 5. The difference indicates the net outflow from the system into the "black box", that was estimated to about 159 421 tonnes of nitrogen (see Appendix A.5) and regarded as adding up the difference. This is not a primary loss, but goes into food consumption, to later end up as a potential loss after sewage treatment.

Figure 8, first presented in Section 2.4, shows the case of the nitrogen flow in today's agricultural system in the UK. The flow ratio was *estimated* to be 0.16 - 0.55, see Appendix A.8, and regarded as low.

Figure 8: Conceptual nitrogen flow through agriculture in the UK today, presented in Section 2.4.

Figure 9 shows the principle of how the flow can be more closed, and by which means, that results from the model system. The flow ratio indicator for this alternative system is 4.7, based on Table 4, i.e. recycling is almost five times the amount of the fertiliser input need. This shows a substantial improvement from the current system in the UK. If recycling of wastewater could be quantified and included, this would improve the model flow ratio further by offsetting most of the fertiliser input need.

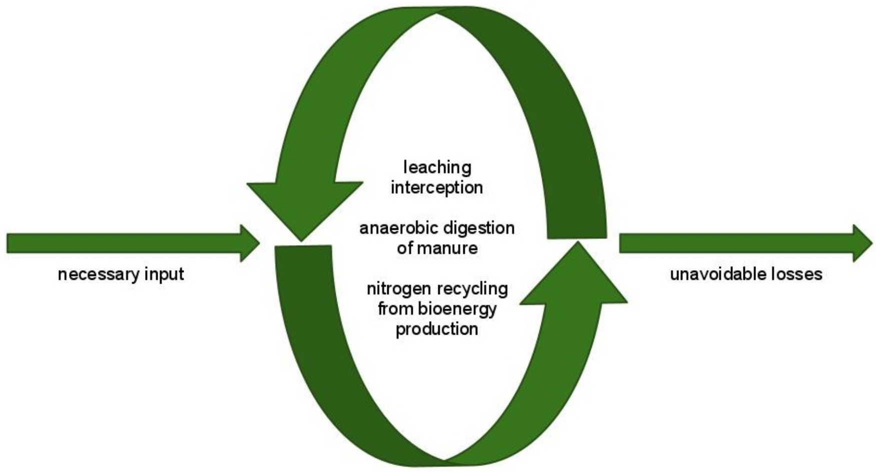

Figure 9: Conceptual nitrogen flow in the alternative model system, with flow ratio indicator = 4.7

5 Sensitivity analysis

The Basic scenario in the model system is optimistic but technically possible; assumptions about yields and other parameters are chosen to be conservative, and collected and based on assessments in many sources. However, some parameters build on more far-reaching assumptions about technology and management implementation. The sensitivity analysis models a smaller implementation of four parameters regarding biomass production and end routes, and manure recycling potential, and their separate influence on the results. The variations create something similar to four different scenarios. For data and calculations, see Appendix B. There is also a general description of other assumptions and uncertainties that could affect the model results.

5.1 Scenario comparison of 4 sensitive parameters

5.1.1 "Grazing"

In reality, grazing grassland is regarded as a simple and economic way to feed cattle. The grasslands in the UK have been adapted to this production system, and so have the livestock breeds. Even if some livestock today are given a grain-based feed, grazing is the preferred praxis. Keeping livestock inside all year round may present a health risk to the animals, as well as to quality of life. Therefore, this analysis will test the influence on the model results if 40% of cattle-LSU are grazed instead of forage fed, to resemble a summer season with grazing for all cattle (pigs and poultry are still kept inside). The manure during grazing is lost from the model system. For simplicity, cattle are grazed on parts of the switchgrass and alfalfa area since these crops are suitable for grazing as well as forage harvest. These areas are fertilised as in the Basic scenario to sustain the high production, and also since the manure from grazed cattle will be unevenly spread on the land with poor incorporation. This parameter change will imply less manure collection from cattle, less biogas production and less nitrogen recycling.

5.1.2 "Anaerobic Digestion"

The Basic scenario builds on total implementation of decentralised on-farm anaerobic digestion (AD) of manure. Full implementation even from a medium-term perspective would require strong policy and effort. This section models an implementation of 50% of the manure that is digested. The non-digested manure is assumed to be collected and spread conventionally on arable land, but with relatively higher nitrogen losses than for the digested manure-nitrogen.

5.1.3 "Co-firing"

In the Basic scenario the end route for bioenergy is ethanol production. However, whether 2nd generation biofuel technology will be implemented in medium-term is uncertain since it depends on the domestic policies for promoting bioenergy vs. other renewable technologies. Since coal is very common for energy production in the UK today, this parameter is modelled as if all the willow would be co-fired with coal in a coal plant, instead of fermented into ethanol. It implies no recycling of nitrogen from this part of the model, but instead a loss as NO_x.

5.1.4 "Bioenergy"

The Basic scenario assumes that all remaining permanent grassland after forage production is suitable for bioenergy production. However, in reality this remaining area may be too poor or sensitive, or physically unreachable to suit a large-scale bioenergy production. This section will model the influence on results if merely 30% of the "remaining grassland" is suitable for willow production.

5.1.5 Comparison

Table 6 shows a comparison of the outcomes from the sensitivity analysis. Results are collected from tables in Appendix B, and the nitrogen flows are normalised on each row to the quantities from the Basic scenario to facilitate comparison. Shares of total energy, transport and gas consumption are also included for comparison between the different scenarios. The flow ratio indicator is presented, based on the principle described in Section 2.4, and a high value means a high recycling compared to fertiliser input. It shall be pointed out that losses are calculated in the same way as in the Basic scenario, i.e. loss to sewage systems from food consumption is *not* included ("black box"). Therefore "Losses" rather reflects a lack in recycling within the *quantified* system.

Table 6: Comparison of sensitivity analysis outcome with Basic scenario.

Feature	**Basic** closing flow	**Grazing** 40% cattle grazing	**AD** 50% impl.	**Co-firing** no nitrogen recyc. bioen.	**Bioenergy** 30% of grassland
Nitrogen flows					
Inflow system	1	1	1	1	0.89
Recycling	1	0.77	0.94	0.72	0.87
Fertiliser need	1	2.1	1.3	2.3	0.78
Losses	1	1.6	1.2	1.7	0.89
Flow ratio	4.7	1.7	3.4	1.5	5.2
Energy					
Of transp. fuel	17%	17%	17%		9%
Of energy consump.				14%	
Of gas consump.	2.4%	1.6%	1.2%	2.4%	2.4%

"Grazing" and "Co-firing" have the smallest flow ratios because of losses of manure when livestock graze or when no recovery of nitrogen in biomass burning occurs. "Bioenergy" has the smallest flows and losses and the highest flow ratio, but also the smallest energy production. This is because the substantially smaller area utilised for bioenergy, compared to the Basic scenario, reduces the amount nitrogen in the system.

The methane from anaerobic digestion of manure contributes to only around a few percent to the total natural gas consumption in all scenarios, but are lowest in "AD" and "Grazing" due to low levels of manure being collected for digestion. All scenarios contribute substantially to meeting the energy demand for the transportation sector (or the overall energy consumption as in the "Co-firing" scenario). The "Co-firing" scenario implies that the leaching-intercepted nitrogen only serves to produce bioenergy, the nitrogen is cascaded one further step and then lost as NO_x, and does not contribute to more a closed flow. The resulting fertiliser input need can be met with the same alternatives as in the Basic scenario: by wastewater recycling in an attempt to almost completely close the flow and/or by fertiliser production with some of the produced biogas.

5.2 Other uncertainties

5.2.1 Import/export and the "black box"

In this study, nitrogen in export and import of food and feed products was not possible to track due to lack of separate data. Therefore, food consumption and feed production were described as a "black box" together with import/export into and out from the UK. However, estimations showed that there was a net outflow of nitrogen from the quantified system into the black box that explained the difference between inflows and quantified losses. Therefore the "black box" did not influence the model result. What is known from the study is that there is an inflow of nitrogen into the UK from imports. The nitrogen in imported products for food consumption end up in sewage, which was described as a potential for additional recycling of nitrogen. If separate data for nitrogen in feed imports had been possible to retrieve, the model could have incorporated additional feed alternatives, for several livestock groups, than those described. This would most probably have influenced the model result and nitrogen flows. The domestic recirculation of reactive nitrogen could have increased if there had been a switch from imports to domestic feed production. Now the model conceals feed-nitrogen, imported from an agricultural system with unknown nitrogen performance.

5.2.2 NO_x deposition, NH_3 volatilisation and N_2O emissions

Influence of NO_x deposition from air, originating in anthropogenic combustion, was not included in the quantification of nitrogen flows. As stated in Section 2.1.2, the deposition is on average 17 kg_N per hectare annually [4]. This inflow most certainly has an influence on fertilisation of ecosystems, but it is unevenly spread due to rainfall patterns. However, if it had been included it could have indicated where there is an additional fertilisation of agricultural land.

Section 2.1.2 also presented ammonia volatilisation and deposition in connection to fertiliser or manure spreading, and that those losses normally are high. While the model described a more efficient manure management, some ammonia losses through volatilisation were included. Those were quantified as a pure systems loss, and their possible influence on yields when depositing back onto land was not assessed. If this influence could have been identified, it could have affected the model results, by for example offsetting some fertiliser need.

Finally, it shall be mentioned that N_2O was left out of the modelling completely. While N_2O is a strong greenhouse gas, it is not a reactive form of nitrogen that is useful for agriculture, and the comparable flows of it are small. However, since N_2O is released both from soils but also in fertiliser production, a quantification could have identified additional flows of nitrogen in the socio-agricultural system, and provided options for improvement and reductions.

6 Discussion

6.1 The importance of managing the nitrogen flow

It was proposed already in 1999 that the anthropogenic nitrogen fixation must be managed, for example by a cap and trade system [66]. While this would regulate the inflow to the system, it lacks thinking about the losses and how to minimise them. The background research in this thesis shows that it is important to control the flow of reactive nitrogen. The losses to the environment, and the resulting environmental impacts, are significant and the recycling of nitrogen can contribute to mitigating these impacts. A close integration of food, feed and fuel production to increase recycling and efficiency has also been proposed before [47, 102]. However, only few sources propose utilisation of nitrate in wastewater for increased system efficiency, e.g. Eickhout *et al.* [35]. This thesis set out to create a more closed flow of nitrogen in the socio-agricultural system in the UK, with maintained food and livestock production. The results show how it is possible to meet both food and bioenergy demand while decreasing the losses of reactive nitrogen and increase the recycling. The key to achieve a more closed flow lies in an increased recirculation of nitrogen from waste flows, i.e. in manure and bioenergy production residue, but also from human sewage waste.

One measure that supports the above stated importance to control the nitrogen flow, is the flow ratio indicator that was developed in this study. The indicator shows the recycling in comparison to the needed fertiliser input to the socio-agricultural system. In the current system, the flow ratio is between 0.16 - 0.55 and regarded as very low. In all the model scenarios, the indicator showed values from over 1 and up to over 5. Therefore, the technologies and management implementations discussed below could have a substantial influence on improving the nitrogen situation.

Critique on the indicator may be that is does not take into account the nitrogen inflow to the agricultural system through biological nitrogen fixation by legumes. This may be a quantitatively important inflow, but was not included in the indicator since the fixation is biological and does not require natural gas and is not causing emissions of CO_2 or N_2O [103]. It is also important to consider that a very high flow ratio may indicate that there is a high amount of nitrogen circulating around in the system. The larger the amount reactive nitrogen in the system, the larger the risk of losses, and an increased amount of reactive nitrogen in the system might be undesirable. Therefore, while this thesis only focused on a closing of the flow, reducing the flow of reactive nitrogen may be as important, as for example was exemplified in the scenario with less bioenergy production. Finally, the flow ratio indicator is assumed to have provided a relevant measure to compare the recycling performance of the model scenarios.

6.2 Implications on agriculture and efforts needed

One of the measures in this thesis for mitigated nitrogen losses was leaching interception from cropland. The leaching was intercepted by a perennial bioenergy crop, in this case willow, but it could have been a forage crop like switchgrass as well. The results show that the leaching from cropland can be intercepted to a large extent, but for some crops, e.g. wheat with high input and leaching, the field ratio causes a very high load to the perennial alleys and buffer strips. The resulting final loss was the largest of the model losses, but lower than an older leaching figure for only England and Wales.

While riparian zones in current agriculture serve mainly as a denitrification area, the leaching interception subsystem in the model also produces bioenergy. However, perennial buffer zones can be seen as an "end-of-pipe" solution to nitrate leaching, that does not contribute to increased recirculation of reactive nitrogen. As have been mentioned before, the soil dynamic is not so fully understood as to provide management practices that eliminates nitrate leaching. If it was possible to "engineer" the agricultural soils and fertilisers to provide the right amount of plant-available nitrogen in the right moment this problem could be solved. It is also uncertain whether a more "natural" management of soils with legume fixation and organic fertilisers could provide optimal nitrogen concentration for required yields, or if inorganic controlled fertilisation will be necessary anyway. Losses from soils occur regardless if they are fertilised with organic or inorganic nitrogen [8]. Higher nitrogen use efficiency in crop production and heavily reduced leaching are the ultimate goals, both to mitigate environmental impact but also losses of valuable nitrogen from the agricultural system. While waiting for research to help improve nitrogen use efficiency, cellulosic perennial crop integration is a simple strategy to mitigate nitrogen leaching and provides a feedstock for bioenergy or forage production.

Integration of perennial bioenergy crops as leaching interception would require a major rearrangement of cropland, but the actual planting of crops is closer at hand to implement compared to the alternatives of developing precision farming, and improving knowledge about soil dynamics sufficiently to guide changes in agronomic practices and drastically reducing nitrogen losses. The concept of buffer strips is not something new for agriculture and farmers, and therefore an expansion of buffer strips is seen as a realistic option. This type of nitrogen management with bioenergy production might also provide a cost-efficient alternative to restoration of wetlands. Both buffer strip plantations and wetlands may in addition provide valuable habitats in the landscape, thereby improving the landscape. Their relative attractiveness in this regard will vary depending on the character of the landscape.

Introduction of bioenergy production on remaining grassland contributed to the biofuel potential in the model. As the scenarios in the sensitivity analysis show, this extra production that requires fertilisation contributes to large flows of nitrogen. As mentioned above, high amounts of reactive nitrogen in the system increase the risk for losses. Since bioenergy can be fertilised with nitrate-rich wastewater, this combination of bioenergy production and wastewater cleaning in a multifunctional system may be the best option for fertilisation of bioenergy, so that chemical fertilisers are not required.

The end-route for bioenergy also has implications for the nitrogen flow. As the model results show, 2nd generation biofuel technologies allow for nitrogen recycling, while co-firing of biomass with coal implies that the nitrogen in the biomass is emitted as NO_x emissions. These emissions contribute to tropospheric ozone formation, and have subsequent impact on acidification and eutrophication when depositing with rainfall over land or sea. From a nitrogen-recycling perspective, co-firing of biomass is not desirable. 2nd generation technologies have a broad spectrum of possible fuels that can be obtained through the gasification process and may, next to ethanol fermentation from cellulosic biomass, become important in the future. For example, biomass could be converted into biodiesel and other fuels used in agriculture. This could be a route for agriculture to be self-producing in fuel and decrease the dependence on fossil energy and impact on climate change [11]. Since 2nd generation technologies are not fully commercial yet, their implementation would require a policy effort to steer production and technologies towards this, instead of towards 1st generation food-crop-based technologies that is the case today. 2nd generation technologies are therefore in the medium or long term and a realistic implementation is still uncertain. Cellulosic bioenergy is an uncertain element in the strive to close the nitrogen flow since the end routes heavily influence the system recycling performance, but it still offers a large potential if implemented.

This thesis did not focus on the concrete implementation of wastewater recycling to land as a technology, but rather on wastewater as an important part of the anthropogenically induced flows, and as a nitrogen source. The results show that recycling of wastewater could contribute to an almost closing of the flow, and that bioenergy could be a suitable target to filter this water without concerns for disease. However, in an efficient system these bioenergy areas would have to be adjacent to wastewater treatment works to facilitate infrastructure when irrigating with wastewater. The feasibility was outside the scope of this thesis and is therefore unknown. However, since nitrate loads to water systems still are high and wastewater treatment (bacterial denitrification of nitrate) is costly, vegetation filters, such as willow, would be worth to evaluate further.

6.3 Policy recommendations for nitrogen

The background research in this thesis outlined some of the current policies in the agricultural field: CAP is rewarding behaviour that reduces environmental impact and the Nitrates Directive regulates accepted levels of nitrate in watercourses and improved nitrogen practices. Introduction of NVZs was supposed to mitigate nitrate levels through regulation of when, how and where nitrogen fertiliser or manure can be applied, but nitrate levels are still high. The UK Biomass Strategy pay little attention to nitrogen. Even if recycling of nitrogen has gotten more attention, these policies do not reflect a systems perspective on the nitrogen flow. The results in this thesis show that nitrogen recycling can give a very important contribution to mitigating the losses of reactive nitrogen to the environment, and to reduce chemical fertiliser input. From a policy perspective there is a need for a connection of several agricultural policies. If the nitrogen flow shall be controlled, such a policy must join the different parts of society that deals with or causes the large flows and losses of nitrogen: primarily fertiliser use and livestock management, but also biofuel technologies for biomass end routes and wastewater treatment. A nitrogen policy should therefore be developed so that it also stimulates implementation of technologies and practices that improve the nitrogen recycling, such as anaerobic digestion and 2nd generation biofuel technologies. Also, targeted bioenergy policies could contribute to improving the nitrogen management and recycling. To conclude, there is a need for a systems perspective on nitrogen, and maybe also a systemic change of the agricultural arrangement.

6.4 Future research

Due to lack of separate data for production and import of cattle feed additives that would have been necessary to discount that from the crop production, this thesis did not consider options for changing the livestock feeding system but only exchanged grazing for forage. It shall be mentioned that the cattle production in the UK depends heavily on protein-rich feed additives, such as soybean meal or maize, domestically produced on cropland or imported [81]. The import need could be reduced by introducing feed legumes (such as soybean) in off-season winter-cropping, but that can have a negative impact on leaching [104]. And the short growing season during winter in the UK does not allow for sufficient yields. Feed crops like maize require high-input agriculture with large nitrogen losses. However, protein concentrates can be extracted from a juice pressed from the green parts of protein-rich perennial grasses (for example alfalfa), called Leaf Protein Concentrates (LPC) [105]. This process leaves a residue that can be feedstock for cellulosic ethanol production [102]. An implementation of this process could decrease the need for high-input feed crop production, as well as dependence on imports. Since alfalfa is also a nitrogen-fixing legume, LPC production could have a positive impact on the nitrogen flow (less fertiliser to cropland and no fertiliser on alfalfa). Therefore, there are further options available than those shown in the model that could reduce the impact from livestock management and feed production on nitrate losses.

Another measure to improve feed production efficiency worth mentioning is the AFEX[16] process [102]. This is a pretreatment of cellulosic material that makes it highly digestible, for ruminants or for ethanol fermentation. Such a process could improve the nutritional value of forage, or the process yield of biofuel production, in the future. The process is also an option for co-production of feed and bioenergy since the same crops can be used. This could have a positive impact on reduced losses to manure through improved protein accessibility and uptake from the forage, and decreased dependence on fossil energy sources. AFEX treatment and LPC feed are options that should be included in future research about the nitrogen flow in agriculture, particularly in livestock and cellulosic bioenergy research.

Future research should also investigate further these questions: Are there other options for nitrogen recycling than through gasification of fermentation residue and digestate with nitrogen recovery? Will 2nd generation technologies on biomass be the preferred option for bioenergy? How feasible could implementation of wastewater recycling to land be? How could a nitrogen-focused policy be formulated to integrate the discussed aspects? If other nutrients (like potassium and scarce phosphorus) are taken into account, are there better options available to control all nutrient flows efficiently together?

[16] Ammonia Fiber EXpansion

7 Conclusions

Based on the research and model results, this thesis concludes the following:

- The nitrogen flow in agriculture can be more closed than today, and recirculation of reactive nitrogen in the socio-agricultural system can contribute to reducing nitrogen losses to surrounding ecosystems, causing eutrophication

- Integration of cellulosic perennial crops is a simple strategy for significantly mitigating nitrate leaching from cropland

- Implementation of technologies and practices that allow for more efficient nitrogen recycling in manure management and bioenergy production is crucial for controlling the nitrogen flow

- Recycling of wastewater to agricultural land could further offset some of the fertiliser need and is therefore an important measure to investigate

- A systems perspective on the nitrogen flow and integration of nitrogen-related policies with bioenergy policies could be essential for reaching a sustainable nitrogen flow

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A Model calculations

This appendix aims at keeping to standard units throughout the equations, for example metric tonnes (t), litres (L), cubic metres (m^3), Joules (J), year (yr), tonnes oil equivalents (toe). Hectares (ha) will be used as area unit due to its common and convenient use in the agricultural disciplines. Data in other units have been converted upon extraction. Indexes are explained in connection to actual calculations.

A.1 Cropland, leaching, and integration of willow

Table 7 shows detailed areas for arable crops [67], nitrogen input rate [18], total input and nitrogen lost after leaching interception. Peas and beans are legumes that fix their own nitrogen, with a fixation rate of 100 $\frac{kg_N}{ha \cdot yr}$ [106]. The rest of the crops need applied nitrogen fertiliser. The input need for the first 8 categories in Table 7 is based on nitrogen input rate if manure is *not* applied, to reflect actual input needed to sustain yield. This data was not available for the last 5 categories, and data for average fertiliser input (with possible extra manure use) for each of these crops was used.

Calculation of field ratio for willow interception to crop land:

$$\frac{\text{temporary grassland}}{\text{arable land}} = \frac{1.232\ Mha}{4.390\ Mha} = 0.2806... \approx 28\% \tag{1}$$

Example calculation for "Wheat" (all crop calculations follow this principle):

$$(\frac{0.192\frac{t_N}{ha \cdot yr} \times 0.4}{0.28} - 0.1\frac{t_N}{ha \cdot yr}) \times (0.28 \times 1.939 \cdot 10^6 ha) = 0.0946232 \cdot 10^6 \frac{t_N}{yr} \tag{2}$$

The negative values for "Roots+fodder beet" and "Other feed crops" in the "Lost" column in Table 7 signify a lower load to willow than the assumed 0.1 $\frac{t_N}{ha \cdot yr}$. How low is it?
"Roots and fodder beet":

$$\frac{0.061\frac{t_N}{ha \cdot yr} \times 0.4}{0.28} = 0.08714...\frac{t_N}{ha \cdot yr} \tag{3}$$

"Other feed crops":

$$\frac{0.029\frac{t_N}{ha \cdot yr} \times 0.4}{0.28} = 0.04142...\frac{t_N}{ha \cdot yr} \tag{4}$$

Equations 3 and 4 shows how low the load to willow is. These values are 41% and 87% of the assumed willow uptake of 0.1 $\frac{t_N}{ha \cdot yr}$. However, since this occurs on 1.4% of the arable area ($\frac{0.028+0.034}{4.39} \approx 1.4\%$), the influence on the total willow yield per year is assumed insignificant and neglected.

Integrated willow will absorb 0.1 $\frac{t_N}{ha \cdot yr}$ from cropland-leached nitrogen, totalling:

$$0.1\frac{t_N}{ha \cdot yr} \times 1.232 \cdot 10^6 ha = 0.1232 \cdot 10^6 \frac{t_N}{yr} \tag{5}$$

Table 7: Arable crop areas [67], fertiliser input [18], total fertiliser input, and lost nitrogen after interception.

Crop	**Area** $10^6 ha$	**N** $\frac{t_N}{ha \cdot yr}$	**TotN** $10^6 \frac{t_N}{yr}$	**Lost** $10^6 \frac{t_N}{yr}$
Wheat	1.939	0.192	0.372288	0.0946232
Barley (winter)	0.383	0.142	0.054386	0.0110304
Barley (spring)	0.539	0.107	0.057673	0.0079772
Oilseed rape (winter)	0.622	0.191	0.118802	0.0301048
Oilseed rape (spring)	0.020	0.123	0.00246	0.000424
Potatoes	0.138	0.185	0.02553	0.006348
Sugar beet	0.118	0.101	0.011918	0.0014632
Maize	0.164	0.081	0.013284	0.0007216
Peas, dry harv	0.042	*0.1 (fix)*	0.0042	0.000504
Field beans	0.166	*0.1 (fix)*	0.0166	0.001992
Oats	0.124	0.090	0.01116	0.000992
Rye/corn/triticale	0.029	0.102	0.002958	0.0003712
Linseed	0.044	0.074	0.003256	0.0000704
Roots+fodder beet	0.028	0.061	0.001708	(-0.0001008)
Other feed crops	0.034	0.029	0.000986	(-0.0005576)
Total	**4.390**		**0.697209**	**0.156622**
of which, fixation			*0.0208*	

A.2 Livestock, grazing and feed production

A.2.1 Livestock units

Table 8 shows in detail the livestock numbers in the UK in 2010 [67], presented and recalculated into Livestock Standard Units (LSU). The factors are adapted and mixed from several sources [72, 73, 74, 75]. The choice to modify the coefficients was based on a test where the livestock data was matched to different coefficient tables and the total results differed by 50% (between 10-15 million LSU). Therefore a mix of coefficients were chosen to align with the trend of declining numbers the recent decade [15]. The final total was compared to 13.88 million LSU in 2007 [107] and regarded as valid. Excluded livestock categories are deer, camelids and other animals, a total of 40 000 heads (less than 2% of total number).

One Livestock Standard Unit (LSU) is by FAO[17] defined as the intake of a 500 kg cow with 13 months calving interval, producing 3500 kg milk each lactation period [108]. That is defined to an annual metabolisable energy (ME) intake of 35600 MJ, including carbohydrates, proteins and fibres.

Feed is often classified by total digestible nutrients (TDN) which is a weight measure representing the sum of energy, proteins, fibres and other nutrients that is available to the animal [109]. ME is $\sim$ 80% of TDN on an energy basis [110] and the energy content of TDN is 4.4 $\frac{kcal}{g_{TDN}}$ [110, 80]. 1 kcal is 4148 J.

[17] Food and Agriculture Organisation of the United Nations

The energy need for 1 LSU is converted:

$$\frac{35600 \cdot 10^6 \frac{J}{LSU \cdot yr} \times \frac{1}{0.8}}{4148 \frac{J}{kcal} \times 4.4 \frac{kcal}{g_{TDN}} \cdot 10^6 \frac{g}{t}} = 2.438195845 \frac{t_{TDN}}{LSU \cdot yr} \tag{6}$$

Table 8: Livestock numbers in the UK in 2010 [67], conversion factors [72, 73, 74, 75] and total LSU per category.

Category	$10^6 heads$	LSU factor	$10^6 LSU$	$10^6 LSU$
Ruminants				
Cattle				
- Dairy cows	3.308	1	3.308	
- Other	6.805	0.7	4.7635	
				8.0715
Sheep and goats	31.177	0.1		3.1177
Non-ruminants				
Pigs				
- Breeding	0.518	0.4	0.2072	
- Other	3.942	0.2	0.7884	
				0.9956
Poultry				
- Table chicken	105.309	0.0045	0.4738905	
- Breeding + laying	47.107	0.008	0.376856	
- Other poultry	11.451	0.015	0.171765	
				1.0225115
Horses	0.311	0.8		0.2488
Total LSU				**13.4561115**

A.2.2 Rough grazing for sheep and goat

In Equation 7, grazing for sheep and goats are calculated based on the chosen stocking density of 0.60 $\frac{LSU}{ha}$. The result shows that all 3.1177 $M\ LSU$ of sheep and goats from Table 8 fit well on the rough grazing areas.

$$0.60 \frac{LSU}{ha \cdot yr} \times 5.283 \cdot 10^6 ha = 3.1698 \cdot 10^6 LSU \tag{7}$$

A.2.3 Forage production from switchgrass and alfalfa

Swichgrass has a nutrient content of 0.55 $\frac{t_{TDN}}{t_{DM}}$ and crude protein content (CP) of 0.075 $\frac{t_{CP}}{t_{DM}}$ [84, 85, 86, 87]. Yield is chosen to 10 $\frac{t_{DM}}{ha \cdot yr}$ [82, 83].
Thus, $\frac{0.075}{0.55} = 0.13636... \approx 0.136 \frac{t_{CP}}{t_{TDN}}$.
Alfalfa nutrient content is 0.66 $\frac{t_{TDN}}{t_{DM}}$, protein 22 $\frac{t_{CP}}{t_{DM}}$ and yields vary [80, 88], so 10 $\frac{t_{DM}}{ha \cdot yr}$ is chosen.
Again, $\frac{0.22}{0.66} = 0.3333... \approx 0.333 \frac{t_{CP}}{t_{TDN}}$

Ratio of switchgrass and alfalfa, on a TDN basis, to supply 20% CP:

$$0.20 = 0.333 \cdot x + 0.136 \cdot (1 - x) \rightarrow x = 0.32.. \approx 0.32 \tag{8}$$

32% of the forage diet shall come from alfalfa, and 68% from switchgrass.

How many Mha of switchgrass and alfalfa is needed to support 8.0715 M cattle-LSU, based on the TDN intake in Equation 6 and the other data?

Switchgrass:

$$2.438195845\frac{t_{TDN}}{LSU \cdot yr} \times 0.68 \times \frac{8.0715 \cdot 10^6 LSU}{0.55\frac{t_{TDN}}{t_{DM}} \times 10\frac{t_{DM}}{ha \cdot yr}} = 2.433150996 \cdot 10^6 ha \quad (9)$$

Alfalfa:

$$2.438195845\frac{t_{TDN}}{LSU \cdot yr} \times 0.32 \times \frac{8.0715 \cdot 10^6 LSU}{0.66\frac{t_{TDN}}{t_{DM}} \times 10\frac{t_{DM}}{ha \cdot yr}} = 0.9541768612 \cdot 10^6 ha \quad (10)$$

Nitrogen input for switchgrass is 0.120 $\frac{t_N}{ha \cdot yr}$ [83, 89, 90], adjusted from backtracking CP content in Equation 11. N content in proteins is 16%, i.e. conversion factor between crude protein and N content is 1/0.16 = 6.25 [111].
Calculation backwards from CP content to see necessary input for switchgrass:

$$\frac{10\frac{t_{DM}}{ha \cdot yr} \times 0.075\frac{t_{CP}}{t_{DM}}}{6.25\frac{t_{CP}}{t_N}} = 0.12\frac{t_N}{ha \cdot yr} \quad (11)$$

Total nitrogen input for switchgrass:

$$2.433150996 \cdot 10^6 ha \times 0.12\frac{t_N}{ha \cdot yr} = 0.2919781195 \cdot 10^6 \frac{t_N}{yr} \quad (12)$$

Biological N-fixation by alfalfa, that is relevant for the flows in the model, as input to the system, calculated as backtracking from crude protein content:

$$\frac{0.9541768612 \cdot 10^6 ha \times 10\frac{t_{DM}}{ha \cdot yr} \times 0.22\frac{t_{CP}}{t_{DM}}}{6.25\frac{t_{CP}}{t_N}} = 0.3358702551 \cdot 10^6 \frac{t_N}{yr} \quad (13)$$

A.3 Bioenergy production

Yield of willow is 12 $\frac{t_{DM}}{ha \cdot yr}$ based on [32, 60, 70, 91, 92].
Biomass production of integrated-willow (cropland leaching interception):

$$1.232 \cdot 10^6 ha \times 12\frac{t_{DM}}{ha \cdot yr} = 14.784 \cdot 10^6 \frac{t_{DM}}{yr} \quad (14)$$

Remaining grassland area in model, from Table 1 in Section 3, and Equations 9 and 10:

$$5.925 \cdot 10^6 ha - 2.433150996 \cdot 10^6 ha - 0.9541768612 \cdot 10^6 ha = 2.537672143 \cdot 10^6 ha \quad (15)$$

Biomass production of bioenergy-willow on remaining grassland:

$$2.537672143 \cdot 10^6 ha \times 12\frac{t_{DM}}{ha \cdot yr} = 30.45206572 \cdot 10^6 \frac{t_{DM}}{yr} \quad (16)$$

Bioenergy-willow nitrogen input need:

$$2.537672143 \cdot 10^6 ha \times 0.1 \frac{t_N}{ha \cdot yr} = 0.2537672143 \cdot 10^6 \frac{t_N}{yr} \quad (17)$$

2nd generation biochemical route for ethanol production from willow biomass. Results in Equation 14 and 16 with conversion efficiency of 300 $\frac{L_{eth}}{t_{DM}}$ adapted from [47, 93], yields ethanol:

$$14.784 \cdot 10^6 \frac{t_{DM}}{yr} \times 300 \frac{L}{t_{DM}} = 4435.2 \cdot 10^6 L \quad (18)$$

$$30.45206572 \cdot 10^6 \frac{t_{DM}}{yr} \times 300 \frac{L}{t_{DM}} = 9135.619715 \cdot 10^6 L \quad (19)$$

How much of the transport fuel in the UK can that cover?
1 metric ton oil equivalent (toe) $\approx$ 42 GJ and 1 $L_{ethanol}$ = 21.1 MJ (LHV) [112]. Total road transportation fuel in 2009 in the UK was 39.667 $Mtoe$ [101].

$$\frac{(4435.2 + 9135.619715) \cdot 10^6 L \times 21.1 \frac{MJ}{L}}{39.667 \cdot 10^6 toe \times 42 \cdot 10^3 \frac{MJ}{toe}} = 0.1718... \approx 17\% \quad (20)$$

Recycling of nitrogen in ethanol production:
82% of exported N [47] - here same as input/uptake of 0.1 $\frac{t_N}{ha \cdot yr}$ - can be recovered. Assume a loss of 10 % when handling and incorporating the ammonia on land. That is a total recovery of $0.82 \times 0.9 = 73.8\%$.
How much nitrogen can be recycled to the agricultural system from integrated-willow and bioenergy-willow ethanol production, based on the nitrogen interception/input to willow from Equation 5 and 17?

$$(0.1232 + 0.2537672143) \cdot 10^6 \frac{t_N}{yr} \times 0.738 = 0.2782018042 \cdot 10^6 \frac{t_N}{yr} \quad (21)$$

Losses from this activity (26.2%).

$$(0.1232 + 0.2537672143) \cdot 10^6 \frac{t_N}{yr} \times 0.262 = 0.0987654101 \cdot 10^6 \frac{t_N}{yr} \quad (22)$$

A.4 Manure processing

A.4.1 Manure production

A dairy cow, i.e. one LSU, excretes 53 $\frac{L_{slurry}}{day}$ [94]. Assume slurry density around 1 $\frac{kg}{L}$ and that is 53 $\frac{kg}{LSU \cdot day}$. The output for other livestock follows the LSU factors so only one figure will be used in the model. That gives around 20 $\frac{t_{manure}}{cow \cdot yr}$, which agrees with other sources that a cow produces 18 $\frac{t_{manure}}{cow \cdot yr}$ [95].

Total amount manure production per year from confined livestock; all cattle, pigs and poultry:

$$0.053 \frac{t}{LSU \cdot day} \times 365 \frac{day}{yr} \times 10.0896115 \cdot 10^6 LSU = 195.1835345 \cdot 10^6 \frac{t}{yr} \quad (23)$$

A.4.2 Methane production from anaerobic digestion of manure

Cow, i.e. LSU, manure has 6.5 weight-% total solids (TS) [97]. Methane potential is 175 $\frac{m^3_{CH_4}}{t_{TS}}$ [97, 98] (losses included). Methane production from anaerobic digestion:

$$195.1835345 \cdot 10^6 \frac{t}{yr} \times 0.065 \frac{t_{TS}}{t} \times 175 \frac{m^3_{CH_4}}{t_{TS}} = 2220.212705 \cdot 10^6 \frac{m^3_{CH_4}}{yr} \quad (24)$$

How much is that of total gas consumption in the UK? Gas consumption was 1000 TWh in 2009 [101]. That is 3.6 $\cdot 10^{12} MJ$. Methane energy content is 39 $\frac{MJ}{m^3}$.

$$\frac{2220.212705 \cdot 10^6 m^3 \times 39 \frac{MJ}{m^3}}{3.6 \cdot 10^{12} MJ} \approx 2.4\% \quad (25)$$

A.4.3 Nitrogen recovery from manure digestion

The nitrogen output in manure is $0.085 \frac{t_N}{LSU \cdot yr}$ (before losses) [94]. Roughly 75% of the nitrogen in feed is excreted in manure [94]. Justify these figures by calculating N intake in Equation 26 and compare with N intake in proteins in Equation 27:

$$\frac{0.085 \frac{t_N}{LSU \cdot yr}}{0.75 \frac{manure}{feed}} = 0.1133... \frac{t_N}{LSU \cdot yr} \approx 0.1 \quad (26)$$

Nutrient intake from Equation 6, where proteins are 24.8% of TDN [80]:

$$\frac{2.438195845 \frac{t_{TDN}}{LSU \cdot yr} \times 0.248 \frac{t_{CP}}{t_{TDN}}}{6.25 \frac{t_{CP}}{t_N}} = 0.0967... \frac{t_N}{LSU \cdot yr} \approx 0.1 \quad (27)$$

The results in Equations 26 and 27 are roughly the same, and the figure of 75% feed nitrogen in excretion regarded as valid.

Recovered nitrogen from manure digestion (15% is lost as ammonia through handling, storage and application):

$$0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU \times 0.85 = 0.7289744309 \cdot 10^6 \frac{t_N}{yr} \quad (28)$$

Losses:

$$0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU \times 0.15 = 0.1286425466 \cdot 10^6 \frac{t_N}{yr} \quad (29)$$

Nitrogen lost from horse manure, that is *not* collected or digested:

$$0.085 \frac{t_N}{LSU \cdot yr} \times 0.2488 \cdot 10^6 LSU = 0.021148 \cdot 10^6 \frac{t_N}{yr} \quad (30)$$

A.5 The 'black box' of food consumption

Estimation of some flows into and out from the "black box" in Figure 7 in Section 4 that is outside the system boundary. Nitrogen in crops with harvest, based on data from Table 7:

$$0.697209 \text{ applied} - 0.1232 \text{ absorbed} - 0.156622 \text{ lost} = 0.417387 \cdot 10^6 \frac{t_N}{yr} \text{ exported} \quad (31)$$

Backtracking of nitrogen that must come from feedstuffs, based on assumed manure-N output and that 75% of intake comes out with manure. For all livestock (10.3384115 M LSU), except sheep and goats. Nitrogen from cattle forage feed from Equations 12 and 13 ($0.3358702551 + 0.2919781195 = 0.6278483746$), is discounted and gives the amount of nitrogen from feedstuffs:

$$\frac{0.085 \frac{t_N}{LSU \cdot yr} \times 10.3384115 \cdot 10^6 LSU}{0.75} - 0.6278483746 \cdot 10^6 \frac{t_N}{yr} = 0.5438382621 \cdot 10^6 \frac{t_N}{yr} \quad (32)$$

There is an outflow from the system boundary of meat products. The nitrogen in meat from cattle, pigs and horses (total 10.0896115 M LSU) will be calculated (25% of feed-N). Nitrogen in sheep and goat meat is not calculated as they are outside the quantified system boundary, and some of them are bred for other products than meat, i.e. wool. Horses are assumed to *not* be bred for meat products. Nitrogen flow in meat into the "black box", calculated from manure output:

$$\frac{0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU}{0.75} \times 0.25 = 0.285872326 \cdot 10^6 \frac{t_N}{yr} \quad (33)$$

Net outflow from the system boundary to the "black box", from Equations 31, 32, and 33:

$$0.417387 \cdot 10^6 \frac{t_N}{yr} - 0.5438382621 \cdot 10^6 \frac{t_N}{yr} + 0.285872326 \cdot 10^6 \frac{t_N}{yr} = 0.159421064 \cdot 10^6 \frac{t_N}{yr} \quad (34)$$

A.6 Fertiliser production from biogas

Various sources give fertiliser yields between 1.1-1.3 [8, 113, 114]. Here 1.2 $\frac{kg_N}{m^3_{CH_4}}$ will be used. How much of the methane production from Equation 24 would be needed to produce the fertiliser need in Table 9 in the following section?

$$\frac{\frac{0.2149780987 \cdot 10^6 \frac{t_N}{yr}}{0.0012 \frac{t_N}{m^3_{CH_4}}}}{2220.212705 \cdot 10^6 \frac{m^3_{CH_4}}{yr}} = 0.0806... \approx 8\% \quad (35)$$

A.7 Nitrogen flow accounting

Tables 9 and 10, corresponding to Tables 4 and 5 in Section 4, show the detailed data of the flows in the Basic scenario, with referencing to calculations.

Table 9: Detailed table of quantified nitrogen flows in the model system.

Activity	**Quantity** ($10^6 \frac{t_N}{yr}$)	**Ref**
Nitrogen input to land		
Arable crops	+ 0.697209	Table 7
- of which, peas and beans fixation	(0.0208)	
Switchgrass	+ 0.2919781195	Eq 12
Bioenergy (willow)	+ 0.2537672143	Eq 17
Alfalfa fixation	+ 0.3358702551	Eq 13
Total	1.578824589	
Recycling		
Manure digestion	- 0.7289744309	Eq 28
Bioenergy production	- 0.2782018042	Eq 21
Net inflow to system	0.5716483538	
Biological fixation		
Peas and beans	- 0.0208	
Alfalfa	- 0.3358702551	
Fertiliser input need	0.2149780987	

Table 10: Detailed table of quantified nitrogen losses from the model system.

Activity	**Quantity** ($10^6 \frac{t_N}{yr}$)	**Ref**
Final loss from arable land	0.156622	Table 7
Manure digestion	0.1286425466	Eq 29
Bioenergy production	0.0987654101	Eq 22
Horse manure	0.021148	Eq 30
Total	0.4051779567	

A.8 Flow ratio calculation

Calculation of annual total fertiliser use *today* in the UK, mentioned in Section 2.2, based on arable tillage crops and grassland application rate of 0.149 and 0.063 $\frac{t_N}{ha \cdot yr}$, respectively [14][18]:

$$0.149\frac{t_N}{ha \cdot yr} \times 4.39 \cdot 10^6 ha + 0.063\frac{t_N}{ha \cdot yr} \times 7.157 \cdot 10^6 ha = 1.105001 \cdot 10^6 \frac{t_N}{yr} \quad (36)$$

The flow ratio is calculated as: $\textit{flow ratio} = \frac{\textit{recycling}}{\textit{fertiliser input}}$

Based on fertiliser input ([14] and Section 2.2.2), results for nitrogen output in livestock from Equations 28 and 29, and the assumption that 20-70% of the nitrogen is truly recycled in the system (the rest lost through poor spreading, no spreading, and direct deposition by grazing) [20, 21], the flow ratio for *current* agriculture in the UK is:

$$\frac{(0.7289744309 + 0.1286425466) \cdot 10^6 \frac{t_N}{yr} \times (0.2 \text{ to } 0.7)}{1.1 \cdot 10^6 \frac{t_N}{yr}} = 0.1559... \textit{ to } 0.5457... \quad (37)$$

Flow ratio indicator for the Basic scenario in the model (calculations in the sensitivity scenarios follow same principle), based on Equations 28 and 21, and Table 9:

$$\frac{(0.7289744309 + 0.2782018042) \cdot 10^6 \frac{t_N}{yr}}{0.2149780987 \cdot 10^6 \frac{t_N}{yr}} = 4.68... \quad (38)$$

[18] Data for Great Britain (England, Wales and Scotland) in 2010, but application rate assumed to be valid for the UK

B Sensitivity analysis

If not stated otherwise, these calculations build on the same extracted data as the corresponding calculations in Appendix A. Data in bold in tables shows the differences compared to the Basic scenario.

B.1 "Grazing"

40% of the cattle-LSU are assumed to be grazed (to resemble a summer season of grazing for all cattle), and their manure will be lost. This will imply less manure collection from cattle, less methane production and less nitrogen recycling. This will affect Equations 23, 24, 25, 35, 28, and 29 from Basic scenario. They are recalculated below.

New, total LSU with manure collection:

$$0.9956 \text{ pigs} + 1.0225115 \text{ poultry} + (8.0715 \text{ cattle} \times 0.6) = 6.8610115 \text{ M} \quad (39)$$

Total amount manure production per year from confined livestock:

$$0.053 \frac{t}{LSU \cdot day} \times 365 \frac{day}{yr} \times 6.8610115 \cdot 10^6 LSU = 132.7262675 \cdot 10^6 \frac{t}{yr} \quad (40)$$

Methane production from anaerobic digestion:

$$132.7262675 \cdot 10^6 \frac{t}{yr} \times 0.065 \frac{t_{TS}}{t} \times 175 \frac{m^3_{CH_4}}{t_{TS}} = 1509.761292 \cdot 10^6 \frac{m^3_{CH_4}}{yr} \quad (41)$$

Percent of gas consumption in the UK:

$$\frac{1509.761292 \cdot 10^6 m^3 \times 39 \frac{MJ}{m^3}}{3.6 \cdot 10^{12} MJ} = 0.01635... \approx 1.6\% \quad (42)$$

Nitrogen recovery from manure digestion and digestate spreading:

$$0.085 \frac{t_N}{LSU \cdot yr} \times 6.8610115 \cdot 10^6 LSU \times 0.85 = 0.4957080809 \cdot 10^6 \frac{t_N}{yr} \quad (43)$$

Losses from manure nitrogen recycling (15%), as ammonia through handling and spreading:

$$0.085 \frac{t_N}{LSU \cdot yr} \times 6.8610115 \cdot 10^6 LSU \times 0.15 = 0.0874778966 \cdot 10^6 \frac{t_N}{yr} \quad (44)$$

The grazing-alternative also has to quantify the loss of nitrogen in the manure from grazing animals. Even if some of the manure will serve to fertilise the grazed switchgrass and alfalfa, it is seen as an inefficient way not directly contributing to yields, and regarded as a system loss (no generation of methane gas or controlled recycling of nitrogen):

$$0.085 \frac{t_N}{LSU \cdot yr} \times (8.0715 \times 0.4) \cdot 10^6 LSU = 0.274431 \cdot 10^6 \frac{t_N}{yr} \quad (45)$$

Table 11: Quantified flows of nitrogen in "grazing".

Activity	**Quantity** $(10^6 \frac{t_N}{yr})$	**Ref**
Nitrogen input to land		
Arable crops	+ 0.697209	Table 7
- of which, peas and beans fixation	(0.0208)	
Switchgrass	+ 0.2919781195	Eq 12
Bioenergy (willow)	+ 0.2537672143	Eq 17
Alfalfa fixation	+ 0.3358702551	Eq 13
Total	1.578824589	
Recycling		
Manure digestion	**- 0.4957080809**	Eq 43
Bioenergy production	- 0.2782018042	Eq 21
Net inflow to system	**0.8049147039**	
Biological fixation		
Peas and beans	- 0.0208	
Alfalfa	- 0.3358702551	
Fertiliser input need	**0.4482444488**	

Table 12: Quantified losses of nitrogen from the model system in "grazing".

Activity	**Quantity** $(10^6 \frac{t_N}{yr})$	**Ref**
Final loss from arable land	0.156622	Table 7
Manure digestion	**0.0874778966**	Eq 44
Grazing manure loss	**0.274431**	Eq 45
Bioenergy production	0.0987654101	Eq 22
Horse manure	0.021148	Eq 30
Total	**0.6384443067**	

B.2 "Anaerobic Digestion"

Implementation of AD is only 50% on a manure basis. The non-digested manure is assumed to be used and spread conventionally on arable land to offset some fertiliser need (corresponding to the same amount of nitrogen). This will affect Equations 24, 25, 35, 28, and 29 from the Basic scenario. They are recalculated below. In this alternative all cattle, pigs and poultry are assumed to be confined inside, as in Basic scenario, for collection of manure.

Total amount of manure production from Equation 23 is 195.1835345 $\cdot 10^6 \frac{t}{yr}$ from confined livestock. Methane production through anaerobic digestion, with only 50% digestion capacity implemented for the collected manure:

$$195.1835345 \cdot 10^6 \frac{t}{yr} \times 0.5 \times 0.065 \frac{t_{TS}}{t} \times 175 \frac{m^3_{CH_4}}{t_{TS}} = 1110.106352 \cdot 10^6 \frac{m^3_{CH_4}}{yr} \quad (46)$$

Percent of gas consumption in the UK:

$$\frac{1110.106352 \cdot 10^6 m^3 \times 39 \frac{MJ}{m^3}}{3.6 \cdot 10^{12} MJ} = 0.0120... \approx 1.2\% \quad (47)$$

Nitrogen recovery from manure digestion and digestate spreading, with 50% collection/digestion capacity:

$$(0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU) \times 0.5 \times 0.85 = 0.3644872154 \cdot 10^6 \frac{t_N}{yr} \quad (48)$$

Losses (15%), as ammonia through handling and spreading:

$$(0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU) \times 0.5 \times 0.15 = 0.0643212733 \cdot 10^6 \frac{t_N}{yr} \quad (49)$$

In this alternative the collected manure that is not digested, is spread conventionally. That also means that storage may be poorer than for manure for anaerobic digestion. Some nitrogen may be lost to air but redeposited on fields, but a general final loss of 30% is used in the calculations to reflect the less efficient manure treatment.
Calculation of nitrogen that is spread:

$$(0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU) \times 0.5 \times 0.70 = 0.3001659421 \cdot 10^6 \frac{t_N}{yr} \quad (50)$$

An the loss from the system (30%):

$$(0.085 \frac{t_N}{LSU \cdot yr} \times 10.0896115 \cdot 10^6 LSU) \times 0.5 \times 0.30 = 0.1286425466 \cdot 10^6 \frac{t_N}{yr} \quad (51)$$

Table 13: Quantified flows of nitrogen in "ad".

Activity	**Quantity** ($10^6 \frac{t_N}{yr}$)	**Ref**
Nitrogen input to land		
Arable crops	+ 0.697209	Table 7
- of which, peas and beans fixation	(0.0208)	
Switchgrass	+ 0.2919781195	Eq 12
Bioenergy (willow)	+ 0.2537672143	Eq 17
Alfalfa fixation	+ 0.3358702551	Eq 13
Total	1.578824589	
Recycling		
Manure digestion	**- 0.3644872154**	Eq 48
Manure conv. spreading	**- 0.3001659421**	Eq 50
Bioenergy production	- 0.2782018042	Eq 21
Net inflow to system	**0.6359696273**	
Biological fixation		
Peas and beans	- 0.0208	
Alfalfa	- 0.3358702551	
Fertiliser input need	**0.2792993722**	

Table 14: Quantified losses of nitrogen from the model system in "ad".

Activity	**Quantity** ($10^6 \frac{t_N}{yr}$)	**Ref**
Final loss from arable land	0.156622	Table 7
Manure digestion	**0.0643212733**	Eq 49
Manure spreading	**0.1286425466**	Eq 51
Bioenergy production	0.0987654101	Eq 22
Horse manure	0.021148	Eq 30
Total	**0.46949923**	

B.3 "Co-firing"

This parameter is modelled as if the willow biomass would be used for co-firing with coal instead of for 2nd generation fuel production. It implies no recycling of nitrogen from this part of the model. Heating value for willow is 19.8 $\frac{GJ}{t_{DM}}$ [70]. When co-firing the biomass, the nitrogen is emitted to the environment as NO_x together with newly fixed nitrogen from air in the combustion process. The nitrogen originating in biomass is calculated as a system loss (but nitrogen originating in air is outside the scope and not quantified). On all other parts the scenario is the same as in Basic scenario.

Take the results from Equation 14 and 16 and calculate energy production:

$$(14.784 + 30.45206572) \cdot 10^6 \frac{t_{DM}}{yr} \times 19.8 \cdot 10^9 \frac{J}{t_{DM}} = 0.8956741013\ EJ \quad (52)$$

How much of the energy consumption can that meet? Energy consumption was 152.746 $Mtoe$ in the UK in 2009 [101].

$$\frac{0.8956741013 \cdot 10^{12} MJ}{152.746 \cdot 10^6 toe \times 42 \cdot 10^3 \frac{MJ}{toe}} = 0.13961.. \approx 14\% \quad (53)$$

Nitrogen from harvest of willow *is not* recycled but lost as NO_x. The loss (from Equation 5 and 17) amounts to:

$$0.1232 + 0.2537672143 = 0.3769672143 \cdot 10^6 \frac{t_N}{yr} \quad (54)$$

Table 15: Quantified flows of nitrogen in "co-firing".

Activity	**Quantity** ($10^6 \frac{t_N}{yr}$)	**Ref**
Nitrogen input to land		
Arable crops	+ 0.697209	Table 7
- of which, peas and beans fixation	(0.0208)	
Switchgrass	+ 0.2919781195	Eq 12
Bioenergy (willow)	+ 0.2537672143	Eq 17
Alfalfa fixation	+ 0.3358702551	Eq 13
Total	1.578824589	
Recycling		
Manure digestion	- 0.7289744309	Eq 28
Co-firing willow	**0**	*per def.*
Net inflow to system	**0.8498501581**	
Biological fixation		
Peas and beans	- 0.0208	
Alfalfa	- 0.3358702551	
Fertiliser input need	**0.493179903**	

Table 16: Quantified losses of nitrogen from the model system in "co-firing".

Activity	**Quantity** ($10^6 \frac{t_N}{yr}$)	**Ref**
Final loss from arable land	0.156622	Table 7
Manure digestion	0.1286425466	Eq 29
Co-firing bioenergy	**0.3769672143**	Eq 54
Horse manure	0.021148	Eq 30
Total	**0.6833797609**	

B.4 "Bioenergy"

This section models the influence on results if only 30% of the "remaining grassland" (from Section A.3) is suitable for willow production. The willow production area will therefore be 2.537672143 $Mha \times 0.3 = 0.7613016429$ Mha. This change affects Equations 16, 19, 20, 17, 21 and 22. Below they are recalculated.

Willow from remaining grassland:

$$0.7613016429 \cdot 10^6 ha \times 12 \frac{t_{DM}}{ha \cdot yr} = 9.135619715 \cdot 10^6 \frac{t_{DM}}{yr} \tag{55}$$

How much ethanol is that?

$$9.135619715 \cdot 10^6 \frac{t_{DM}}{yr} \times 300 \frac{L}{t_{DM}} = 2740.685914 \cdot 10^6 L \tag{56}$$

The renewable potential in the transport sector is calculated together with ethanol from intercepted-willow in Equation 18:

$$\frac{(4435.2 + 2740.685914) \cdot 10^6 L \times 21.1 \frac{MJ}{L}}{39.667 \cdot 10^6 toe \times 42 \cdot 10^3 \frac{MJ}{toe}} = 0.0908... \approx 9\% \tag{57}$$

Nitrogen input need:

$$0.7613016429 \cdot 10^6 ha \times 0.1 \frac{t_N}{ha \cdot yr} = 0.07613016429 \cdot 10^6 \frac{t_N}{yr} \tag{58}$$

How much nitrogen can be recycled to the agricultural system from integrated-willow and bioenergy-willow ethanol production, based on the input to willow from Equation 5 and 58? Recovery is 73.8%.

$$(0.1232 + 0.07613016429) \cdot 10^6 \frac{t_N}{yr} \times 0.738 = 0.1471056612 \cdot 10^6 \frac{t_N}{yr} \tag{59}$$

Losses from this activity (26.2%):

$$(0.1232 + 0.07613016429) \cdot 10^6 \frac{t_N}{yr} \times 0.262 = 0.052224503 \cdot 10^6 \frac{t_N}{yr} \tag{60}$$

Table 17: Quantified flows of nitrogen in "bioenergy".

Activity	Quantity ($10^6 \frac{t_N}{yr}$)	Ref
Nitrogen input to land		
Arable crops	+ 0.697209	Table 7
- of which, peas and beans fixation	(0.0208)	
Switchgrass	+ 0.2919781195	Eq 12
Bioenergy (willow)	+ **0.07613016429**	Eq 58
Alfalfa fixation	+ 0.3358702551	Eq 13
Total	**1.401187539**	
Recycling		
Manure digestion	- 0.7289744309	Eq 28
Bioenergy production	**- 0.1471056612**	Eq 59
Net inflow to system	**0.5251074468**	
Biological fixation		
Peas and beans	- 0.0208	
Alfalfa	- 0.3358702551	
Fertiliser input need	**0.1684371917**	

Table 18: Quantified losses of nitrogen from the model system in "bioenergy".

Activity	Quantity ($10^6 \frac{t_N}{yr}$)	Ref
Final loss from arable land	0.156622	Table 7
Manure digestion	0.1286425466	Eq 29
Bioenergy production	**0.052224503**	Eq 60
Horse manure	0.021148	Eq 30
Total	**0.3586370496**	