PREFACE

This thesis is the result of research that has been conducted in the context of a training thesis at the Center of Energy and Environmental studies, University of Groningen. This report presents the results of long and hard work in the past year. I would like to thank all people who have assisted me during my research. At first, I would like to thank my supervisor, Sanderine Nonhebel, who has helped me to structure the research and has given me a great deal of tips. She has given a lot of comments both related to content as to the structure of the report. Thanks to her I have managed to structure all values found and calculated in such a way that this report is readable and understandable for any IVEM student or staff. Also, I would like to thank all different roommates, especially Sophie Jongeneel, Laura Moria and Manel van der Sleen for their inspiration, motivation, social talks and tips. Moreover, I would like to thank all other IVEM students and staff for any help and discussions during the past year. Especially, I would like to thank Ton Schoot Uiterkamp, who was also my second supervisor, for his valuable lessons on how to read scientific literature critically. I have found many bad articles and the discussions have helped me to distinguish the good from the bad. At last, I want to thank you for reading my report. Upon writing this preface and finishing my report I will continue working on my master thesis and will certainly benefit from this experience and the lessons learnt.
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SUMMARY

Biofuels are thought to be one of the options to substitute fossil fuels and prevent global warming by the greenhouse gas (GHG) effect as they are seen as a renewable form of energy. However, biofuels are almost solely subjected to criticism from an energy and global warming point of view. Since biofuels are produced by agriculture of which environmental impacts are known, it is odd that other environmental impacts are hardly addressed. Many environmental impacts by agricultural production are related to the nitrogen cycle. Humans have already increased nitrogen fertilizer input to the nitrogen cycle to a level beyond natural flows by agriculture. Therefore, from an environmental point of view there is a need for understanding the relation between nitrogen cycle and producing biofuels on a global scale. The main goal of this research is to show the impact of energy cropping on the nitrogen cycle and to compare this to natural flows. The following main research question has been formulated: what will be the global nitrogen requirement for increased biofuel production? To answer this question a literature study has been performed: biofuel production systems, energy crops, nitrogen requirement of crops and energy and GHG balances of various biofuels. The values found in literature have been compared and used to calculate a global nitrogen requirement for biofuel production.

Nitrogen is mostly present in the atmosphere as $N_2$, which is a very stable molecule. While the whole nitrogen cycle consists of many processes, for this study the most important flux is nitrogen fixation, which is the formation of reactive N out of $N_2$. As $N_2$ is very stable it is only reactive nitrogen that actually cycles until eventually $N_2$ is formed again. The average rate at which nitrogen is fixed has already more than doubled due to anthropogenic processes. This has resulted in an environmental burden since the presence of too much reactive N can result in a range of environmental impacts like: loss of biodiversity, eutrophication, global warming, ozone depletion, acidification, air pollution and toxicity.

For the feasibility of the analysis a selection was made among energy crops based on several criteria. At first, substitutes for both gasoline and diesel had to be included. Secondly, various crops were selected based on regional aspects. Thirdly, the major biofuel crops of today have proven to be successful and reliable data is available. At last also a non-food crop has been selected. These criteria have resulted in the following energy cropping systems: biodiesel from rapeseed, ethanol from corn, sugarcane and timber. Some cropping systems are more complex than others. For example sugarcane and timber biofuel systems have only outputs in the form of energy, ethanol and electricity. However, rapeseed and corn biofuel systems also yield material byproducts. Producing solely electricity from timber also has been included in the analysis to compare fuel and electricity production.

Analysis of the production of the various crops showed that yields and nitrogen requirements are quite different. Sugarcane cropping has the highest yield, while rapeseed is produced with the lowest yield. However, rapeseed production also has the highest nitrogen requirement. Corn production also requires a high nitrogen input almost equal to that of rapeseed. Timber cropping has the lowest nitrogen requirement, but has a lower yield than sugarcane production.

The energy and GHG balances for 1 kg of fuel produced by the various systems showed large differences. Ethanol from sugarcane and timber has a relatively much higher net output than fuel produced from rapeseed or corn even if energy credits for non-energy byproducts are included. The GHG balances show a similar picture. Timber shows the highest GHG reduction per kg fuel compared to conventional fuel. Sugarcane also shows a high reduction, while corn and rapeseed biofuels result in only minor GHG emission reductions compared to conventional fuels.

Relating net energy output and GHG reduction to nitrogen input increases the difference between the various cropping systems even further. Low yields, high nitrogen application rates and unfavorable energy and GHG balances result in a low output and GHG reduction per kg N for rapeseed and corn derived biofuels. Sugarcane and timber show a net output and GHG reduction 1 to 2 orders of magnitude higher. These numbers have been used to calculate global nitrogen requirement for the substitution of all conventional fuels or to eliminate all...
GHG emissions in transportation. Timber and sugarcane ethanol can replace conventional fuels and reduce GHG emissions without adding more than another quantity of nitrogen equal to the global natural fixation rate. The amount is still significant, though, 0.3-0.5 times the natural flow. Using rapeseed or corn biofuel, would have a substantial effect on the global nitrogen cycle, resulting in a requirement of nitrogen over 10 times higher than the natural input. Electricity from timber has about 2 times the net energy output and reduction per kg N than that of timber ethanol.

This research has led to three main conclusions. Firstly, from a nitrogen perspective we should mainly use timber and sugarcane instead of corn and rapeseed, if one of these energy crops is going to be used on a large global scale. The second conclusion is that current energy cropping systems need significant nitrogen inputs. Biofuel production will have an impact on the nitrogen cycle in the same order of magnitude as agricultural production so far. The third conclusion is that electricity from timber is far more efficient in reducing GHG emissions. All in all, producing biofuels on a substantial scale will have a significant impact on the nitrogen cycle.
GLOSSARY

BNF - Biological Nitrogen Fixation, formation of reactive N out of N₂ by microorganisms
CO₂-eq - Carbon dioxide equivalent emissions. Other GHG emissions have been converted to CO₂ equivalents.
DDGS - Distillers’ Dried Grain and Solubles, byproduct of producing alcohol, especially used in the corn ethanol industry. It is very suitable as feed for livestock.
Elec. - Electricity
EtOH - Ethanol
GHG - Greenhouse Gas.
ha - Hectare.
HHV - Higher Heating Value
LHV - Lower Heating Value
NH₃ - All forms of reduced inorganic N combined with several H-atoms.
Nitrogen fixation - Breaking N₂ up into reactive N.
NOₓ - All forms of oxidized inorganic N in combination with one or more O-atoms.
Nr - Reactive nitrogen, nitrogen in other forms than N₂.
odt - Oven dried ton.
Redox - Reduction and oxidation reactions.
1. INTRODUCTION

Global warming by greenhouse gas emissions is now generally accepted and seen as a major environmental burden. Globally many countries are setting targets for reduction of greenhouse gas emissions. This reduction mainly has to be achieved by using new renewable energy sources. One of these renewable energy sources are biofuels. Biofuels are seen as a green source of energy because they have a closed carbon cycle. That is, carbon released during combustion was sequestered earlier by photosynthesis. Biofuels are subjected to more and more criticism, however. Many people argue that the energy input during production of biofuels reduces the benefit of these biofuels substantially. Moreover, methane and nitrous oxide emissions during agriculture were not taken into account when the idea of biofuels arose. Some scientists now argue that nitrous oxide emissions negate global warming reduction of biofuels (Crutzen, Mosier, Smith & Winiwarter, 2007). Also, the competition with food raises ethical questions.

The criticism on biofuels today, however, has hardly focused on other environmental issues besides global warming. This is strange, since biofuels are mainly produced by agriculture and it is known that agricultural production results in many environmental impacts. Of these environmental impacts by agricultural production, many are related to the nitrogen cycle. Since the green revolution, mankind has started to influence this nitrogen cycle by boosting agricultural production. The rapid increase in agricultural yield per ha has only been possible by the use of artificial fertilizers. According to both Socolow (1999) and Vitousek et al. (1997) these fertilizers are the major contributor to the flow and stock changes in the global nitrogen cycle, as one of the functions of artificial fertilizer is adding reactive nitrogen forms to arable land to enhance plant growth. Fossil fuel combustion is another big contributor to the alteration of the nitrogen cycle, since nitrous oxides are emitted in this process. Consequently, both food production and energy have increased anthropogenic nitrogen fixation in the past (Galloway, 1998). Due to these anthropogenic additions of fixed nitrogen, the rate at which nitrogen is fixed has roughly doubled its preindustrial value (Socolow, 1999).

The changes in the global nitrogen cycle have already caused environmental damage. Different impacts due to anthropogenic disruption of the nitrogen cycle can be distinguished (Socolow, 1999). At first, there are three impacts related to ecological processes, since nitrogen is vital to life on earth. If there is too little N, ecosystems have limited growth; if there is too much, they can be over productive (Galloway, 1998). Consequently, the increase of fixed nitrogen has resulted in changes in biodiversity over the years (Vitousek et al., 1997). Furthermore, Vitousek et al. (1997) stated “eutrophication in estuaries and coastal sees is one of the best-documented and best-understood consequences of human-altered N cycling”. Also nitrogen in the form of nitric acid can acidify fresh water supplies. Two other impacts caused by changes in nitrogen flows directly influence public health. Nitrogen oxides are air pollutants and too much nitrate in drinking water is unhealthy. On global scale there are impacts as well. Nitrous oxides enhance both the greenhouse effect and the decline in stratospheric ozone. The above stated environmental consequences indicate that we need to pay attention to the nitrogen cycle.

Nowadays our global population is growing fast. We already live with 6.7 billion people on this planet and it is estimated that global population will grow to more than 9 billion before 2050 (United Nations Population Division, 2006, p.ix). To feed all this people we will need to produce much more food in the near future and in order to do this we need even more fertilizers than we are already using. Fujimori and Matsuoka (2007) state that nitrogenous fertilizer use will increase 2.7 times from now to 2050. Furthermore, the International Energy Agency ([IEA], 2005, p. 79) stresses that our increasing population and relative consumption will result in a growth in energy consumption of more than half from now to 2030.
Biofuels are used for energy purposes and mainly produced by agriculture. Both energy consumption and agriculture have been the causes of alteration of the nitrogen cycle. This suggests that biofuels might do the same. Currently, we do not know the relation between the nitrogen cycle and biofuel production, while it has been demonstrated that the nitrogen cycle is important for the environment. Therefore, there is a need for a more clear understanding of the relation between the nitrogen cycle and producing biofuels on a global scale.
2. RESEARCH SCOPE

2.1. Research Aim
The research aim of this research is threefold. At first, it aims at verifying if nitrogen is important for energy cropping. Secondly, it shows what kind of energy cropping systems can best be used to minimize alteration of the nitrogen cycle. At last, the main goal is showing the impact of energy cropping on the nitrogen cycle and comparing this to natural flows.

2.2. Research question
The following question is the main question of this research:

*What will be the global nitrogen requirement for increased biofuel production on a global scale?*

2.3. Sub questions
In order to answer the main question, this study answers the following sub questions:

I. What are the fluxes of the nitrogen cycle and what is their present magnitude?
II. What are major energy cropping systems currently used?
III. What are the nitrogen requirements and yields of various cropping systems?
IV. How do the energy and GHG balances of these cropping systems compare?
V. What is the relation between these energy and GHG balances and nitrogen input?
VI. What will be the nitrogen requirement if these cropping systems are used to meet global energy demand or GHG reduction?

2.4. Boundaries
This study focuses on the extra nitrogen input that comes along with energy cropping. Both the nitrogen requirement itself as the energy and GHG balances are derived from literature. Also, the energy cropping systems are based on literature about current average and best practice.

Land use is not included in this study. It is assumed that enough land is available for the targets set by governments, whether that is true is beyond the scope of this research. Considering land a distinction is made, however, between temperate and tropical regions for cropping systems. It is pointed out that some cropping systems will not be feasible in both regions and that it will be highly unlikely that only one crop will be used for global energy purposes.

The energy and GHG balances are made on a “cradle to grave” basis or on a “well-to-wheel” basis, as it is common called in fuel studies. In GHG balances carbon soil emissions are not included in the analysis, since these values are highly uncertain.

It must also be noted that the results in this study must not be seen as rigid values, but more as an indication. The orders of magnitude are of importance, not the exact numbers. The results show differences between crops for nitrogen requirements and flows. Furthermore, by scaling up the energy cropping systems to global production, the impact on the nitrogen cycle compared to natural flows can be shown. It will not be discussed where this nitrogen will end up. There is consensus that agriculture has altered the nitrogen cycle considerably, which will be discussed in chapter 3. The question here is thus, whether energy cropping will do the same.

2.5. Method
To calculate the impact of biofuel production on the nitrogen cycle, it is necessary to calculate the total extra nitrogen input for global biofuel production. This is based on two aspects, the amount of biofuels that need to be produced and the nitrogen input necessary to produce a certain amount of biofuels. The former can be calculated by dividing future targets by net energy output or GHG emission reduction per kg fuel, while the latter can be obtained by linking nitrogen input to the production of 1 kg of biofuel.
To obtain the relation between nitrogen and the production of 1 kg biofuel, many data on biofuels must be gathered. At first, a choice must be made among all different biofuel systems, since it is impossible to assess all biofuel routes in one study. Next, the production life cycle of the chosen biofuel systems must be known to relate system input to system output. System input can be obtained by analyzing the agricultural side of the biofuel production systems. Here, nitrogen is used as an input. Furthermore, this nitrogen application and cultivation results in an agricultural yield. This yield per quantity of nitrogen can be converted to the production of biofuel per kg nitrogen by using conversion ratios of production systems.

If biofuel output per kg nitrogen input is known, including energy input and GHG emissions will result in the desired energy output and GHG reduction per kg nitrogen. Therefore, energy and GHG balances of the different production systems have to be known. If these are known net energy output and GHG emissions reduction per kg nitrogen can be calculated (Figure 2.1). Dividing the required net output and GHG emission reduction by this value will yield the final nitrogen requirement. This nitrogen requirement can then be compared to natural flows to assess the impact.

In order to obtain the values needed for the calculations above, a literature study has been performed. There is no literature available on nitrogen requirement for biofuels in relation to energy output and greenhouse gases. However, literature on biofuel production systems, energy crops, nitrogen requirement of crops and energy and GHG balances does exist. In this study values from studies in these areas have been combined and calculated as clarified above. For the calculations a spreadsheet model, Microsoft Excel®, has been used.

Figure 2.1. Method for relating nitrogen input to energy cropping systems
3. THE NITROGEN CYCLE

This chapter describes how the nitrogen cycle works and why nitrogen is important for the environment. Moreover, the major nitrogen flows in the nitrogen cycle are quantified. The magnitudes of natural and current anthropogenic flows are necessary for a comparison with the nitrogen input required for biofuels. The backbone of this chapter is based on a chapter about the nitrogen cycle in a Biochemistry handbook written by Galloway (2003).

3.1. Processes of the nitrogen cycle

Nitrogen is essential for life, without it no life form could exist. It is needed for the synthesis of amino acids and proteins. As humans are not capable of synthesizing amino acids themselves, they have to consume other organisms to obtain their amino acids. While lots of organisms are capable of synthesizing amino acids only very few are able to transform atmospheric nitrogen gas into reactive N that can be used by many organisms. Since N is needed for every organism to sustain life, N is readily transported from one life form to the other. But how does this N come available for different life forms and how does it cycle through the earth? This question will be addressed in this paragraph.

Nitrogen can be present in many forms due to the multiple oxidation and reduction (redox) reactions that can occur. Nitrogen has a full valance range and is thus capable of either gaining 3 electrons or losing all 5 electrons. Nitrogen is mainly present in its most stable form, N₂. Due to redox reactions N can be present in its most reduced form NH₄⁺ or in the highest oxidation state NO₃⁻. In the nitrogen cycle nitrogen transforms from one form to the other in a set of redox reactions. Organic N for example, is mostly in a reduced state as NH₃ and is mainly taken up as –C-NH₂. In this paragraph transportation and the most important reactions will be clarified. This is done from a spherical point of view. There are four main earth based spheres important for the nitrogen cycle, namely the atmosphere, biosphere, lithosphere and hydrosphere. Each sphere will be described and its share in the nitrogen cycle will be explained. However, as mentioned earlier, N₂ is the most abundant and stable N compound in the nitrogen cycle and it has to be converted into reactive N (Nr), which is called nitrogen fixation. Therefore, at first these initial reactions are described. Nitrogen fixation can be seen as an input to the nitrogen cycle.

3.1.1. Nitrogen fixation, input to the nitrogen cycle

Because the triple bond in N₂ can only be broken by a large energy input, there are only two natural processes that are able to fix nitrogen which were both mentioned in the former paragraph. These are Biological Nitrogen Fixation (BNF) and an oxidation reaction initiated by lightning. Apart from the natural nitrogen fixation there are also two anthropogenic processes, namely industrial fertilizer production through the so called Haber-Bosch process and fossil fuel combustion. These four processes will all be described in detail.

The first fixation process is BNF, which is done by only a few types of bacteria and blue-green algae in a local anaerobic environment. These microorganisms use a so called nitrogenase enzyme and can either be free-living or in symbiotic form with the roots of higher plants (Galloway, 2003). An example of such a reaction in Legumes is:

\[
2\; N_2 + 6\; H_2O \rightarrow 4\; NH_3 + 3\; O_2
\]

BNF was mainly responsible for the formation of Nr on earth. This naturally occurring process is nowadays present in natural systems, as well as in cultivated systems. Cultivation of legumes and some types of crops like wetland rice stimulate BNF as the former enhances BNF itself, while the latter provides for an anaerobic environment stimulating BNF.

NH₃ is also created by humans. This is done on industrial scale using the Haber-Bosch process. In this process the following reaction takes place:

\[
N_2 + 3\; H_2 \rightarrow 2\; NH_3
\]
This process is carried out under high temperatures and pressures in combination with an iron, aluminium oxide and potassium oxide catalyst. Under these conditions it is possible to break the triple bond and to synthesize ammonia. Currently, nitrogen fixation by the Haber-Bosch process is occurring at an even higher rate than terrestrial BNF (Galloway et al., 2004). Next to nitrogen fixation in the form of producing ammonia, there are also two processes that synthesize NO out of N_2. The first of these two processes is natural and is triggered by lightning. Due to the electrical charges the triple bond breaks and in combination with oxygen, NO can then be formed. This reaction is as follows:

\[ \text{N}_2 + \text{O}_2 + \text{electrical energy} \rightarrow 2 \text{NO} \]  
(Galloway, 2003)

The second NO formation process is due to anthropogenic activity. During the combustion of fossil fuels, circumstances are created under which N_2 in combination with O_2 can react into NO. The energy released during combustion is capable of breaking the triple bond. This results in the following reaction:

\[ \text{N}_2 + \text{O}_2 + \text{fossil energy} \rightarrow 2 \text{NO} \]  
(Galloway, 2003)

Apart from the fixation of atmospheric nitrogen during combustion, NO is also formed due to the nitrogen atoms present in the organic matter, in for example coal. Combustion breaks down the organic chain and if N is present this will thus react with oxygen. Whether this is nitrogen fixation is debatable, but as with carbon dioxide emissions due to fossil fuel combustion this N would not have been released into the nitrogen cycle again if it was not for humans to mine and burn the organic matter (Galloway et al., 2002). These are the four processes responsible for formingNr and they can be seen as input to the nitrogen cycle. After cycling, all Nr eventually ends up as being N_2 in the atmosphere again while these processes continue to fix nitrogen and thus create an input for the cycle as it is only Nr that actually cycles. Now that the nitrogen fixation has been addressed the actual cycling can be described. There are multiple ways in which nitrogen can cycle. From a spherical point of view nitrogen can either cycle within spheres or through spheres. For example, nitrogen fixed in the biosphere by BNF can be converted to organic nitrogen but it can also be emitted into the atmosphere.

3.1.2. Atmospheric processes

The atmosphere is the first sphere to be described, since this is the least complex one. It is mostly controlled by chemical and physical processes and the direct influence of biota is low (Galloway, 2003). By far the largest part of N in the atmosphere is present as N_2, 99.9999% (Winstanley et al., n.d.). Of the remainder 99% of N is made up by N_2O.

The inputs of N to the atmosphere are provided by both anthropogenic and natural sources in one of the other spheres. NO is directly emitted to the atmosphere by combustion processes. NH_3, N_2, NO, and N_2O are emitted through biological processes. Also organic forms of N are taken up by the atmosphere due to for example turbulence or biomass burning (Galloway, 2003). Due to the presence of wind, the atmosphere is capable of transporting N over large horizontal distances. Nitrogen can leave the atmosphere by wet or dry deposition. After emission and before deposition nitrogen compounds in the atmosphere can undergo different reactions, which will be described below. Summarizing, N, once emitted, can be transported horizontally and/or vertically, transformed chemically and/or physically and finally be deposited from the atmosphere (Winstanley et al., n.d.).

Most N is present as the very stable form N_2 which can be fixed, as mentioned earlier. N_2O is also a very stable form and it does not undergo reactions in the troposphere. This is why it has a very long mean residence time in the atmosphere of around 100 years (Galloway, 2003). N_2O is only destroyed once it is subjected to UV radiation in the stratosphere. Here, it reacts into NO according to the following reaction:
\[ \text{N}_2\text{O} + \text{O} \rightarrow 2 \text{NO} \]

Subsequently, NO destroys ozone by multiple reactions after which NO is regenerated:

\[
\begin{align*}
\text{NO} + \text{O}_3 & \rightarrow \text{NO}_2 + \text{O}_2 \\
\text{O}_3 & \rightarrow \text{O} + \text{O}_2 & \rightarrow 2 \text{O}_3 \rightarrow 3\text{O}_2 \\
\text{NO}_2 + \text{O} & \rightarrow \text{NO} + \text{O}_2 
\end{align*}
\]

N\(_2\)O is also a strong greenhouse gas. N\(_2\)O is produced during both nitrification and denitrification processes in the biosphere. It can be concluded that N\(_2\)O emissions contribute to two environmental issues at the same time, namely to the destruction of stratospheric ozone and to the greenhouse effect.

Another oxidized form of N in the atmosphere is NO and is a known pollutant. It quickly reacts to NO\(_2\) in combination with ozone, after which eventually can form an aerosol by several reactions. Such an aerosol can be removed from the atmosphere by deposition.

3.1.3. Cycling in the biosphere

The biosphere consists of all aquatic and terrestrial ecosystems. It has a large influence on the nitrogen cycle. Although the N reservoir in the biosphere is the lowest of all spheres, cycling flows are by far the largest. After all any kind of organism participates in the nitrogen cycle and the amount of organisms is numerous. Especially microbial activity is very important, since it is present in enormous amounts.

Nitrogen is taken up by the biosphere due to BNF, which has already been described. Nitrogen outputs to the atmosphere from the biosphere are N\(_2\), N\(_2\)O, NO and NH\(_3\). Nitrogen is also transported from the biosphere to the hydrosphere as nitrates or ammonium can dissolve in water. And finally organic N is put into the soil (geosphere) due to feces and dead organisms, but this organic N will likely be cycled back quickly into the biosphere due to microbial activity. Transportation within the biosphere occurs by movement of organisms. Other transportation occurs through other spheres.

The number of reactions in which N is involved in the biosphere is enormous and most of them are complex. Several general reactions can be distinguished, however. After nitrogen has been fixed (into NH\(_3\)) it can cycle through different pathways. It can be taken up by organisms into organic N, which is called (ammonia) assimilation or it can be oxidized into nitrate.

Nitrate can either be reduced to ammonia and taken up again by organisms or it can be reduced in a denitrification process via NO and/or N\(_2\)O to N\(_2\) eventually. Organic N is converted back into NH\(_4^+\) by microorganisms during decomposition. This is called ammonification.

3.1.4. Nitrogen in the lithosphere

The lithosphere is the solid outermost shell of the earth. The largest part of the N present in the lithosphere is not available to the nitrogen cycle. However, due to extraction of fossil fuels humans add a lot of nitrogen stored in sedimentary rocks to the active nitrogen cycle. The most important reservoir of N in the lithosphere to the nitrogen cycle is the soil. Large amounts of organic N are present here, but the amount of N in soils varies widely. N is often the limiting nutrient in soils, therefore N fertilization is mostly necessary.

3.1.5. Cycling through the hydrosphere

The fourth sphere is the hydrosphere, which consists of liquid and solid water present on the earth. The interaction with the other spheres is described by the water cycle. Soluble N compounds, like NH\(_4^+\), NO\(_2^-\), NO\(_3^-\) and soluble organic N, are a large source of N for the hydrosphere, but also particulate organic and inorganic N can be transported by water.
3.2. The nitrogen cycle before anthropogenic disturbances

The processes involved in nitrogen cycling are now known. It is also interesting to look at the magnitude of the reservoirs and fluxes. The largest reservoir of N present in the nitrogen cycle (N in the crust and mantle is neglected) is the atmosphere. Almost 80% of all nitrogen is present in the atmosphere, which is equal to $3.9 \cdot 10^9$ Tg N (Galloway, 2003; Winstanley et al., n.d.; Krug & Winstanley, 2002; Lerman, Mackenzie & Ver, 1993). The amount of N in other reservoirs is uncertain as it is very hard to measure. However, estimations have been made on the size of these reservoirs. Sedimentary rocks are considered the second largest reservoir and is around 4 times as low as the atmospheric reservoir (Galloway, 2003). The biosphere contains about 4 orders of magnitude less N than the atmosphere (Winstanley et al., n.d.; Galloway, 2003) and is therefore very small compared to the other two reservoirs mentioned. The last important reservoir is the ocean, in which a part from the biota and also a lot of N is present as dissolved N ($N_2$ and $NO_3^-$), together this reservoir is in between the amount present in the atmosphere and the terrestrial biosphere.

As discussed earlier, nitrogen fixation synthesizes reactive N. Therefore, these fluxes are described first. Galloway and Cowling (2002) have described the nitrogen cycle before industrial anthropogenic interruptions (1890). Biological Nitrogen Fixation was about 100 Tg N yr$^{-1}$ for the terrestrial system and 120 Tg N yr$^{-1}$ for the oceanic system. A more recent estimate by Galloway et al. (2004) sets the BNF prior to anthropogenic times to 128 Tg N yr$^{-1}$ and the rate in 1860 to 120 Tg N yr$^{-1}$. Furthermore, lightning fixes nitrogen at a rate of 5.4 Tg N yr$^{-1}$. There was already a slight anthropogenic addition to the cycle as cultivation enhanced BNF with an extra 15 Tg N yr$^{-1}$ (Galloway et al., 2004). Fossil-fuel combustion could almost be neglected at that time, since it was around 0.6 Tg N yr$^{-1}$ (Van Aardenne et al., 2001).

The next type of flows are emissions. That is, transport from the hydro-, bio- or geosphere to the atmosphere. There are different emissions of N, which are emissions of NO$_x$, N$_2$O, N$_2$, and NH$_3$. Obviously there were also fluxes from the atmosphere to the other spheres as well, atmospheric deposition. Both emissions and depositions are summarized in Figure 3.1. The fluxes mentioned above, were the most important fluxes of the nitrogen cycle at the end of the 19th century. All important fluxes are summarized in Figure 3.1:

![Figure 3.1 - Global nitrogen cycle before anthropogenic interruptions, 1860 (Galloway et al., 2004)](image_url)
3.3. The current nitrogen cycle

The current nitrogen cycle looks a lot different from the nitrogen cycle one century ago. This is due to the intensification of the flows by human actions. At first, the extra input of N to terrestrial systems by using artificial fertilizers was around 100 Tg N yr\(^{-1}\) (Galloway et al., 2004) in the early 1990s and 121 Tg N yr\(^{-1}\) in 2006 (IFA, 2007). Furthermore, the use of fossil fuels has resulted in a NO\(_x\) input of 24.5 Tg N yr\(^{-1}\) during the early 1990s. Terrestrial Natural Biological Nitrogen fixation has decreased to about 107 Tg N yr\(^{-1}\), while BNF enhanced by cultivation has risen to 31.5 Tg N yr\(^{-1}\) according to Galloway et al. (2004). Consequently, the fixation rate to terrestrial systems has almost doubled. Therefore, it can be concluded that mankind has an enormous influence on the global nitrogen cycle.

![Figure 3.2 - The current global nitrogen cycle, early 1990s (Galloway et al., 2004)](image)

The enhancement of Nr formation has also resulted in an increase of other flows. For example, NO\(_x\) emissions have approximately doubled and terrestrial NH\(_3\) emissions are now about 5 times as high as 100 years ago (Galloway et al, 2004). As well as emissions, depositions have changed with a factor 3 to 4. All these changes result in a new global nitrogen cycle, that can be depicted as in Figure 3.2.

3.4. Consequences of nitrogen cycle alteration

While nitrogen is essential to life, it can have multiple environmental impacts. Socolow (1999) states that seven impacts can be identified for the disturbance of the nitrogen cycle. The first impact has to do with the mostly present N-limitation in natural ecosystems. When N becomes abundant in a certain ecosystem, biodiversity reduces. Organisms that were adapted to low levels of nitrogen then face heavy competition by other organisms that before could not survive due to low levels of nitrogen. The second impact is eutrophication, rapid plant growth can be the result of very high levels of reactive nitrogen in certain places. The next two impacts are due to the emission of N\(_2\)O (nitrous oxide) as this is both a greenhouse gas and is capable of destroying stratospheric ozone. N\(_2\)O has an 100-year average global warming potential that is 296 times larger than an equal mass of CO\(_2\) (Prather et al., 2001). Although the total global warming potential of CO\(_2\) is higher due to a much higher amount present in the atmosphere, N\(_2\)O is still an important greenhouse gas. N\(_2\)O is very stable, it has a residence time of 120-years (Socolow, 1999) due to its lack of reactivity. N\(_2\)O is only destroyed in the stratosphere by energetic UV-light. In this reaction NO is formed which...
reacts further to destroy ozone. Fifth impact is acidification by nitrate ions. The last two impacts directly influence human health. Nitrogen oxides are known air pollutants and nitrates in drinking water is toxic, especially for infants.

Moreover, as nitrogen becomes reactive it can contribute to multiple impacts. This is called the nitrogen cascade showed in Figure 3.3. This cascade shows all impacts nitrogen can have before it is denitrified back to \( N_2 \). An example of this cascade is the following. A nitrogen atom fixed from \( N_2 \) by the Haber-Bosch process can be used as fertilizer among others as it was originally developed for gunpowder production. After fertilizer application leaching can occur and nitrogen can be transported to a lake where it can cause eutrophication after which it can be nitrified to nitrate. This nitrate can then contribute to acidification. Next, it could be denitrified to nitrous oxide which ends up in the stratosphere to destroy ozone, and so forth. This example shows that once a nitrogen atom is reactive it can cycle to contribute to all different impacts until it is eventually denitrified to \( N_2 \).

As can be seen from this section, nitrogen is both a very important nutrient as a potential environmental burden. Since we are probably going to increase our inputs to the nitrogen cycle in the coming decades, we should pay attention to this phenomenon from an environmental point of view. To reduce fossil fuel needs humans are increasing the use of biofuels. Current biofuels, though, are produced in the same way as our food, by agriculture. Since agriculture has had and will continue to have a major impact on the nitrogen cycle, biofuels might do exactly the same. Therefore, it is interesting to see to what extent this will be true. This will be analyzed in the following chapters.
4. ENERGY CROPPING SYSTEMS

The previous chapter has shown how nitrogen cycles through the environment, why it is important and the impact of agriculture so far. In order to be able to see the impact of biofuels on the nitrogen cycle, this chapter describes the different energy cropping systems from “cradle to grave” or as is common for fuels, from “well to wheel”.

4.1. Method

Assessing biofuels for their nitrogen impact requires knowledge of how these biofuels are produced. Therefore, biofuel production systems need to be described. That is, to relate nitrogen input to biofuel output, it must be known how that output is obtained. Before these systems can be described, however, a choice of systems has to be made, since it is not possible to assess all possible biofuel routes in one study.

In this chapter a grounded choice is made among the different biofuel systems. Next, the production chains are drawn and in- and outputs are shown. An output can either be the desired energy carrier or a byproduct. Byproducts are also dealt with in this study since part of the inputs ends up in these products and they thus influence the energy and GHG balances. In this study for byproducts an energy and GHG credit is calculated. This credit is based on the product that it will replace. The energy and GHG emissions related to the production of that product will be used to calculate a credit for the biofuel route.

At the end of this chapter it is possible to identify the biofuel routes and the outputs. This will be necessary to link the nitrogen input to the desired output. To quantify this link conversion values for from the agricultural products to the eventual biofuels are mentioned. In the following chapters the link between nitrogen and desirable output will be quantified further.

4.2. Choosing among different energy crops

More and more crops are developed for renewable energy purposes. It would be beyond the scope of this research to incorporate all energy crops in the analysis. Therefore, a selection has been made on different criteria. In road transportation currently two fuels are dominating the market: gasoline and diesel. Ethanol is the common alternative for gasoline, while biodiesel is the most common alternative for conventional diesel. Consequently, at least one biodiesel and bioethanol crop is selected. Next to the type of fuel, for agriculture also regional aspects are important. Most crops do not grow everywhere around the globe or at least not with high yields. Climate is a very important factor for cropping yields and therefore a distinction is made between the tropics, cold temperate and warm temperate regions. At last, crops can also be selected based on current production levels. Since one of the aims of this study is to indicate the impact of a biofuel production increase will result in significant changes to the nitrogen cycle, scaling up currently produced and accepted crops is logical. Furthermore, data on these systems tend to be more reliable than data on potential crops.

Combining the criteria mentioned above, the following three energy crops can easily be selected: sugarcane in the tropics for bioethanol production, rapeseed in colder climate regions for biodiesel production and corn for bioethanol in warmer temperate regions. All three selected crops, however, are also used for food purposes. It is therefore also interesting to analyze woody crops which are not in competition with food and have a high carbon to nitrogen ratio (Keoleian & Volk, 2005). Of the four crops analyzed only sugarcane is a nitrogen fixing crop (Kennedy, Choudhury & Kecskés, 2004). That is, only sugarcane is able to form reactive nitrogen out of the atmosphere by itself. It is interesting to see how this influences the amount of nitrogen fertilizer needed.

4.3. Rapeseed to biodiesel production system

In Europe a lot of rapeseed is cultivated for energy purposes. These rapeseeds are converted to oil from which biodiesel can be produced. From the seeds, oil is obtained by mechanical extraction followed by extraction using an organic solvent (Halleux, Lassaux, Renzoni and Germain, 2008). The remainder, rapeseed cake, can be used as animal feed and is therefore a useful byproduct. Consequently, for rapeseed derived biodiesel a positive energy and GHG
credit will be calculated. This will be done by calculating the amount of cultivated animal feed that can be replaced by this byproduct. In this study wheat is used as a reference for cultivated animal feed.

The oil derived from rapeseed can be refined and first reacts with fossil methanol or ethanol to produce rapeseed methyl ester and glycerin (Halleux, Lassaux, Renzoni & Germain, 2008) after which biodiesel is produced (Figure 4.1).

Different conversion ratios for rapeseed to oil and rapeseed cake can be obtained from different sources (Table 4.1). In this study an oil production of 410 kg / ton rapeseed and a rapeseed meal production of 570 kg / ton will be used as a reference based on the region where most rapeseed production is present and the rest of the analysis is applied to. Harding, Dennis, Blottnitz and Harrison (2007) have studied different cases of biodiesel production. From these different cases either 991 or 947 kg oil is used for the production of 1 ton biodiesel depending on whether methanol or ethanol is used. The extra mass in biodiesel comes from the added alcohol. In this study it is assumed that methanol is the alcohol used in biodiesel production. Around 10 %\textsubscript{mass} of glycol is produced along with 1 ton of biodiesel. In The Netherlands this by-product, glycol, is either combusted, gasified or used as a feedstock to produce methanol again (Prof. dr. ir. G.F. Versteeg, personal communication, August 19, 2008). Therefore, it can be assumed that methanol input and glycol output more or less cancel out based on energy. Consequently, in this study neither energy input nor output will be included concerning methanol and glycol. Now that all conversions from rapeseed to biodiesel are known, an overall yield from rapeseed to biodiesel can be calculated (Table 4.1).

For the energy and GHG credit which will be calculated later on along with the balances, it is important to know the amount of wheat that can be replaced by 1 kg rapeseed cake. This is based on the feed quality. In The Netherlands a scale has been developed by the Dutch Central Bureau for Livestock Feeding (CVB) for the animal feed quality (nutritive value) of all kind of agricultural products. For pig feed a so called EW-value indicates the quality of the animal feed for pigs. The EW-value of rapeseed cake is 0.72 (Duynie, 2008), while the EW-value of wheat is 1.11 per kg product (CVB, 2003). Of course the credit given to biodiesel only makes sense if rapeseed cake can actually replace wheat. If more rapeseed cake is produced than wheat can be replaced, the byproduct would change to waste and a credit should not be given. The credit indicates how this byproduct influences the system, it is beyond the scope of this study to investigate to what extent it is possible to use rapeseed cake as animal feed instead of cultivated products.
### Table 4.1 - Conversion ratios for rapeseed to oil

<table>
<thead>
<tr>
<th>Crop</th>
<th>Main product</th>
<th>By-product</th>
<th>kg output / kg crop</th>
<th>MJ output / kg crop</th>
<th>Remarks</th>
<th>Derived from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed</td>
<td>Diesel</td>
<td>Cake</td>
<td>0,39</td>
<td>0,54</td>
<td>Europe</td>
<td>Reijnders &amp; Huijbrechts, 2008; Harding et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>Cake</td>
<td>0,394-0,404</td>
<td>0,59</td>
<td>World average</td>
<td>FAPRI, 2007; Harding et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>Cake</td>
<td>0,414-0,424</td>
<td>0,57</td>
<td>European average</td>
<td>FAPRI, 2007; Harding et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>Cake</td>
<td><strong>0,414</strong></td>
<td><strong>0,57</strong></td>
<td>Used in study</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>EtOH</td>
<td></td>
<td>0,292</td>
<td></td>
<td>Colombia</td>
<td>Agrocadenas, 2006</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td></td>
<td>0,322</td>
<td></td>
<td>Dry-milling</td>
<td>FAPRI, 2008</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td></td>
<td>0,316</td>
<td></td>
<td>Wet-milling</td>
<td>FAPRI, 2008</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td></td>
<td>0,339</td>
<td></td>
<td>Dry-milling; Future outlook</td>
<td>FAPRI, 2008</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td></td>
<td>0,326</td>
<td></td>
<td>Wet-milling; Future outlook</td>
<td>FAPRI, 2008</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td>DDGS</td>
<td>0,322</td>
<td>0,33</td>
<td>Dry milling</td>
<td>Kim and Dale, 2008</td>
</tr>
<tr>
<td>MeOH</td>
<td>DDGS</td>
<td></td>
<td><strong>0,322</strong></td>
<td><strong>0,33</strong></td>
<td>Used in this study</td>
<td></td>
</tr>
<tr>
<td>Corn stover</td>
<td>EtOH</td>
<td></td>
<td>0,268</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar-cane</td>
<td>EtOH</td>
<td>Elec.</td>
<td>0,068</td>
<td></td>
<td>Anhydrous; Brazil</td>
<td>Macedo et al., 2008</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td>Elec.</td>
<td>0,071</td>
<td></td>
<td>Hydrous; Brazil</td>
<td>Macedo et al., 2008</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td>Elec.</td>
<td>0,073</td>
<td></td>
<td>Brazilian average</td>
<td>FAPRI, 2008</td>
</tr>
<tr>
<td>Timber</td>
<td>EtOH</td>
<td></td>
<td>0,293</td>
<td>7,9</td>
<td></td>
<td>Adler, Delgrosso, &amp; Parton, 2007</td>
</tr>
<tr>
<td>(poplar)</td>
<td>EtOH</td>
<td>Elec.</td>
<td>0,296</td>
<td>8,0</td>
<td>0,77</td>
<td>Faaij, 2006</td>
</tr>
<tr>
<td></td>
<td>EtOH</td>
<td></td>
<td>0,341</td>
<td>9,1</td>
<td>1,54</td>
<td>Faaij, 2006</td>
</tr>
<tr>
<td></td>
<td>Elec.</td>
<td></td>
<td><strong>7,0-7,1</strong></td>
<td></td>
<td>Future outlook</td>
<td>Heller et al., 2004</td>
</tr>
</tbody>
</table>

### 4.4. Corn to ethanol production system

Corn is currently used as a feedstock in the United States for ethanol. Government goals are to increase the amount of ethanol produced significantly in the coming decades. The energy corn production is under heavy debate due to rising food prices. Others also argue that ethanol corn does not make sense from an energy point of view.

Ethanol production from corn is based on the fermentation of starch. Starch first has to be enzimatically treated to obtain glucose syrup. This sugar containing syrup can be fermented into ethanol. There are two ways of corn milling (grinding): wet and dry (Kim and Dale, 2005; Kim and Dale 2008). Wet milling separates the corn grain into different components of which the ethanol is fermented and the remainder sold as co-products. In dry-milling processes, the grains are not separated into components and both enter the process.
completely. The starch is fermented and the nutrients are concentrated into a distilled co-product which is used in animal feed (Sánchez and Cardona, 2008).

Different conversion ratios for both dry- and wet-milling processes can be found (Table 4.1). Kim and Dale (2008) state that over 60% of the ethanol currently is produced by dry-milling, while FAPRI (2008) numbers show that even over 80% is produced by dry-milling. Moreover, new corn-ethanol production sites are mostly based on dry-milling (Tiffany & Eidman, 2003; Kim & Dale, 2008). Therefore, as a reference a dry-milling conversion ratio is used.

Dry milling of corn results in a side-product (Kim & Dale, 2008). This is called distillers’ dried grain and solubles (DDGS) and is fed to livestock like rapeseed cake. It is produced at a rate of 0.33 kg per kg corn (Kim & Dale, 2008). For DDGS it can also be calculated what amount of wheat can be replaced by DDGS. The EW-value of DDGS of maize is comparable with dried brewer’s grain, which has an EW-value of about 0.82 per kg dry matter (CVB, 2003; Duynie, 2006).

Next to corn, its cultivation also yields corn stover. This stover can be left in the field, but using second generation technologies it is also possible to produce ethanol from it (Sheehan et al., 2003). If this route is included, the corn based ethanol systems changes. Sheehan et al. (2003) state that per ton of corn stover, 340 Liters of ethanol can be produced. The lignin part produces a surplus of heat and electricity through co-generation. The corn-based ethanol system is summarized in Figure 4.2, while conversion ratios used in this study can be found in Table 4.1.

Figure 4.2 - Schematic overview of the production chain of biodiesel from corn

4.5. Sugarcane to ethanol production system
Sugarcane is the main feedstock for ethanol production (Sánchez & Cardona, 2008). It is mostly produced in Brazil. However, also in other countries in tropical regions, such as India, China and Sub-Saharan countries, production is increasing (Faaij, 2006). Sugarcane is grown on arable land in tropical areas. The sugarcane itself is harvested and made available for extraction, while the residues, also called sugarcane trash, like the top of the plant and its
leaves, are either left or burned in the field. In conventional sugarcane cultivation the trash is burned, while in more sustainable cultivation sugarcane trash is left in the field. In Brazil in 2002 approximately 80% of all sugarcane trash was burned (Macedo, Silva & Leal, 2004). This share is decreasing, however. In 2008 (Macedo, Seabra, & Silva, 2008) only 70% of the trash was burned.

During extraction, a sucrose containing juice is obtained from the sugar cane (Smeets et al., 2008), which is subsequently fermented to an ethanol solution. The remainder, bagasse, is burned for energy supply to the ethanol production process. The energy output of this combustion process is high enough to generate a surplus of electricity and heat (Macedo et al., 2008; De Oliveira, Vaughan & Rykiel, 2005). With the information above it is possible to draw up a scheme for the sugarcane ethanol system (Figure 4.3). In literature different conversion ratios can be found for sugarcane to ethanol. In this study the actual production data for Brazilian ethanol is used as a reference (Table 4.1).

![Figure 4.3 - Schematic overview of the production chain of ethanol from sugarcane](image)

### 4.6. Timber crops to ethanol or electricity production system

Wood is one of the oldest fuels known to man. Nowadays wood can simply be combusted to generate electricity, but also second generation technologies can be used to produce ethanol from it. The former pathway is quite simple and consists of only two steps. The first step is cultivation. The second step is combusting wood and generating electricity from it. This second step can be carried out in several ways. Wood can be combusted in a furnace to drive a steam turbine, but a more sophisticated and efficient way to generate electricity is using a gasification step prior to combustion. In this way wood is gasified first after which it is more efficiently combusted. The energy efficiency of a biomass gasifier are in between 36-37.2% (Heller, Keoleian, Mann, & Volk, 2004).

The second route is producing ethanol from wood. Ethanol can be produced by fermenting sugars. Wood does not contain such sugars, however. Therefore, the wood has to be treated first, in order to obtain fermentable sugars. This process is carried out by using enzymes, which convert the cellulose and hemi-cellulose part of wood into glucose, xylose and other sugars (Faaij, 2006; Sheehan et al., 2003). This glucose can be fermented into ethanol by yeast. Woody material also consists of a lignin part, which cannot be converted into fermentable sugars. This part can be burned to generate electricity and heat. Surplus electricity can be delivered to the grid.
Again for the timber production system different conversion ratios can be obtained (Table 4.1). All energy conversion ratios are based on the lower heating value (LHV) of ethanol, which is equal to 26.8 MJ / kg (Quirin, Gärtner, Pehnt & Reinhardt, 2004). The energy cropping system of ethanol derived from wood crops can be summarized as depicted in Figure 4.4.

### 4.7. How to deal with electricity as a byproduct

In the sugarcane and timber ethanol production system electricity and heat are produced along with the ethanol. Since ethanol is the desired product of this system, electricity and heat are byproducts. For the corn and rapeseed system the byproduct is used as animal feed and the energy used in the production of wheat is credited. On the contrary electricity is not a material byproduct and can, therefore, not be dealt with in the same manner. However, electricity is an energy output just as ethanol and all the energy inputs in the energy balance. The only problem is that electricity is not the main and desired output.

In this study electricity is treated as follows. The electricity output is added to the net output of ethanol. This results in the output of ethanol 26.8 MJ / kg (Quirin et al., 2004) minus all energy inputs needed to produce ethanol plus the electricity produced (Figure 4.5). If the amount of electricity produced is higher than the energy inputs, the net energy output can be higher than the 26.8 MJ / kg. This method has been chosen, since the generation of electricity also results in the substitution of any form of fossil fuel. In the GHG balance ethanol is credited for the average amount of CO₂ produced by the same quantity of electricity on the grid.

### 4.8. Comparison of different biofuel systems

In this chapter the four chosen production systems have been described. Some are clearly more complex than others. It can be seen that the energy from sugarcane and timber systems only have outputs in the form of energy, while from rapeseed and corn also material byproducts are derived. Furthermore, it can be seen that the production of 1 kg sugarcane ethanol requires much more feedstock than the other routes. The rapeseed production system is the most efficient in converting agricultural product into biofuel. This is, however, only a part of the total production chain. The agricultural production stage will be addressed in the next chapter.
5. NITROGEN REQUIREMENTS AND YIELDS OF ENERGY CROPS

The preceding chapter has shown the different production chains of energy cropping systems and conversion ratios for biofuel production from agricultural products. In this chapter the agricultural part of the chain will be described. Crop yields will be mentioned as well as nitrogen requirements will be quantified.

5.1. Method

The production systems are known, but in order to understand the relation between output and nitrogen requirements it is necessary to know the agricultural side of the production chain. That is, it must be known what nitrogen requirements are for different production routes. Therefore, nitrogen requirements for different crops must be obtained as well as production yields.

In this chapter both these issues are addressed. Where possible yields per ha are obtained from actual production data, if not values from other studies are used. Nitrogen requirements are preferably obtained by using actual application rates practiced in farming, but else from other studies. In order to check whether these application rates are sufficient in meeting the nitrogen requirements for each crop a soil nitrogen balance is established. If this nitrogen balance is close to zero it can be concluded that the application rate is sufficient. Next to the energy crops also cultivation of wheat will be described. The nitrogen requirements and yields of wheat are needed later on in the analysis for the calculation of a energy and GHG credit for animal feed byproducts.

At the end of this chapter it is possible to compare the agricultural production systems at the beginning of the biofuel routes. Moreover, the different energy crops can be compared on the amount of nitrogen needed to obtain a certain yield. This comparison will show nitrogen demands of various biofuel crops.

5.2. Rapeseed yields and nitrogen requirement

Rapeseed yields vary per location. Yield ranges are shown in Table 5.1. In this study a relatively high European yield of 3 ton/ha is used, since new dedicated energy cropping will probably be carried out by the most sophisticated agricultural knowledge available and only makes sense in regions suitable for rapeseed cropping. Apart from the seeds also rape straw is produced. These straws are often left in the field, however, to maintain soil fertility (Boehmel, Lewandowski & Claupien, 2007). The regeneration of nutrients by leaving the straw is not sufficient to maintain a high yield of rapeseed.

Table 5.1 - Rapeseed cultivation yields

<table>
<thead>
<tr>
<th>Yield (ton/ha)</th>
<th>Region</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5-3.2</td>
<td>Europe, 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>2.9-4.1</td>
<td>Germany, 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>3</td>
<td>Europe</td>
<td>Reijnders &amp; Huijbregts, 2008</td>
</tr>
<tr>
<td>3</td>
<td>Europe</td>
<td>Used in this study</td>
</tr>
</tbody>
</table>

To supply the soil with sufficient nutrients, nitrogen fertilizer is applied at a high rate of 165 kg N / ha / year in Germany (Rauh, 2007). To establish a nitrogen balance nitrogen contents of the plant must be known. Different values for N-content are shown in Table 5.2.
Table 5.2 - N-content of rapeseed

<table>
<thead>
<tr>
<th>Part of the plant</th>
<th>N-content (% on mass of yield)</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeds</td>
<td>3.5</td>
<td>Velthof &amp; Kuikman, 2000</td>
</tr>
<tr>
<td>Seeds</td>
<td>3.1</td>
<td>Fismes, Vong, Guckert &amp; Frossard, 2000</td>
</tr>
<tr>
<td>Residue</td>
<td>2.0</td>
<td>Velthof &amp; Kuikman, 2000</td>
</tr>
<tr>
<td>Residue</td>
<td>1.6</td>
<td>Fismes, et al., 2000</td>
</tr>
</tbody>
</table>

Velthof and Kuikman (2000) show that in the seeds per kg 35 g N is present. Another study of Fismes, et al. (2000) shows multiple values of N-content in rapeseed. Calculation results in an average value of about 31 g N per kg seed. This study uses an in between value of 33 g N per kg seed for the nitrogen balance. Therefore, the whole plant takes up 99 kg N / ha / year through seeds and around 53 kg N / ha / year through residues. The former is actually removed from the field, while the latter is regenerated. Consequently, the net supply of N to the soil through agriculture is 66 kg N.

There are, however, more nitrogen flows like N-deposition, leaching and denitrification. On average a loss in fertilizer-N of around 50% occurs (S. Nonhebel, personal communication, June 13, 2008). This is, however, very site-specific. Deposition rates over Germany are used, since the analysis is based on production in that area. Soil N seems to be slowly increasing according to the numbers used (Figure 5.1). This indicates that the application rate of 165 kg N / ha / year is sufficient in the long-run.

Figure 5.1 – Overview of soil nitrogen balance for rapeseed cultivation

5.3. Corn yields and nitrogen requirement

Average corn yields vary highly around the globe (Table 5.3). The yields in this study are based on United States yields, since most corn ethanol production takes place in the US corn-belt. Most of the corn cultivation in the corn-belt is done in a corn-soybean rotation (Kim & Dale, 2005). In this study I look at dedicated systems for a certain energy purpose and, therefore, do not take any rotation crops into account. Consequently, it is assumed that a corn cropping system solely consists of corn to produce ethanol.
Table 5.3 - Corn cultivation yields

<table>
<thead>
<tr>
<th>Yield (ton/ha)</th>
<th>Region</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2-4.9</td>
<td>World</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>8.1-10</td>
<td>United States</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>8.5</td>
<td>United States</td>
<td>Used in this study</td>
</tr>
</tbody>
</table>

According to Kim and Dale (2005), Sheehan et al. (2003) and Kadam and McMillan (2003) approximately as much corn stover, which is all the above ground parts except for the grain, as actual corn grain is produced. From this corn stover currently over 90% is left in the fields (Glassner, Hettenhaus & Schechinger, 1999; Kadam & McMillan, 2003), which is equal to a removal of 10%. The amount of corn stover that can be removed sustainably from the field is estimated by many and varies widely per study. Some residue has to remain on the field to protect the soil against erosion. Furthermore, soil fertility can be enhanced by leaving stover in the field. A life cycle study has shown that Soil Organic Matter (SOM) declines slightly in the early years of stover collection, but remains constant in the long run (Parton, Brenner & Sheehan, 2002). The amount of stover that can be collected sustainably depends on multiple factors, like tillage practice, topography, soil type and crop rotation (Kadam & McMillan, 2003). Possible sustainable removal rates are shown in Table 5.4.

Table 5.4 - Amount of corn stover that can be removed sustainably

<table>
<thead>
<tr>
<th>Removal rate (%)</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-60</td>
<td>Glassner, et al. (1999)</td>
</tr>
<tr>
<td>30</td>
<td>USDA guidelines</td>
</tr>
<tr>
<td><strong>40</strong></td>
<td><strong>Used in this study as sustainable removal rate</strong></td>
</tr>
</tbody>
</table>

As mentioned earlier corn is a non-N\textsubscript{2}-fixing crop (Ramos, Villatoro, Urquiaga, Alves, & Boddey, 2001). Therefore, nitrogen application rates are high, from 2001 to 2003 on average 157 kg N / ha /year is applied in the United States Corn Belt. To establish a nitrogen balance also the N-contents of corn have to be known. Different data on N-contents can be found and are summarized in Table 5.5.

Table 5.5 - N-content of corn and corn stover

<table>
<thead>
<tr>
<th>Part of the plant</th>
<th>N-content (% of yield)</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above ground biomass</td>
<td>1.01</td>
<td>Simulated, Ma et al., 2007</td>
</tr>
<tr>
<td>Above ground biomass</td>
<td>0.89</td>
<td>Measured, Ma et al., 2007</td>
</tr>
<tr>
<td>Corn product</td>
<td>1.34</td>
<td>Simulated, Ma et al., 2007</td>
</tr>
<tr>
<td>Corn product</td>
<td>1.10</td>
<td>Measured, Ma et al., 2007</td>
</tr>
<tr>
<td>Corn product</td>
<td>1.39</td>
<td>Velthof &amp; Kuikman, 2000</td>
</tr>
<tr>
<td>Corn stover</td>
<td>0.78</td>
<td>Simulated, Ma et al., 2007</td>
</tr>
<tr>
<td>Corn stover</td>
<td>0.77</td>
<td>Measured, Ma et al., 2007</td>
</tr>
<tr>
<td>Corn stover</td>
<td>0.7</td>
<td>Velthof &amp; Kuikman, 2000</td>
</tr>
<tr>
<td><strong>Corn product</strong></td>
<td><strong>1.3</strong></td>
<td><strong>Used in this study</strong></td>
</tr>
<tr>
<td><strong>Corn stover</strong></td>
<td><strong>0.75</strong></td>
<td><strong>Used in this study</strong></td>
</tr>
</tbody>
</table>

From the nitrogen content of corn nitrogen removal from the field can be calculated. All nitrogen flows to and from the soil are shown in Figure 5.2. Removing 40% of corn-stover for
ethanol production instead of the 10% that is removed nowadays, decreases the net addition by 19 kg N / ha, which implies that additional fertilizer is needed upon stover removal. Spatari, Zhang and MacLean (2005) state an extra nitrogen input of 7.5 kg N / ton of removed stover is needed. This compares well with the 0.75 % mass N removed, but if losses occur it might have to be higher.

5.4. Sugarcane yields and nitrogen requirement
Sugarcane is grown in the tropics. Yields are much higher than rapeseed and corn (Table 5.6). Yields differ per location, but in this study the Brazilian yields are used since this is the main production region and the whole analysis is based on this region.

Table 5.6 - Sugarcane cultivation yields

<table>
<thead>
<tr>
<th>Yield (ton/ha)</th>
<th>Region</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>68.7</td>
<td>Brazil 2002</td>
<td>Macedo et al., 2004</td>
</tr>
<tr>
<td>72.5</td>
<td>Brazil 2005/2006</td>
<td>Macedo et al., 2008</td>
</tr>
<tr>
<td>70-73</td>
<td>Brazil 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>65</td>
<td>World average 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>80+</td>
<td>Australia 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>100+</td>
<td>Zambia 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td><strong>72.5</strong></td>
<td><strong>Brazil</strong></td>
<td><strong>Used in this study</strong></td>
</tr>
</tbody>
</table>

Sugarcane is a somewhat different crop than for example rapeseed, since nitrogen is fixed by sugarcane cultivation through certain bacteria living in the roots, stems and leaves of the plant (Kennedy, Choudhury & Kecskés, 2004). Therefore, less N-fertilizer is needed to supply the plant with sufficient nitrogen. Furthermore, sugarcane is different from cereal crops as excess available N can reduce sugar content. Average fertilizer application rates in Brazil are on average 60 kg N / ha / year (Macedo, et al., 2008). N-contents of sugarcane are presented in Table 5.7.

Table 5.7 - N-content sugarcane

<table>
<thead>
<tr>
<th>Part of the plant</th>
<th>N-content (% mass)</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh sugarcane (30% dry matter)</td>
<td>0.09</td>
<td>Thorburn et al. (2007)</td>
</tr>
<tr>
<td>Residues (dry matter)</td>
<td>0.45</td>
<td>Based on range Robertson and Thorburn (2007)</td>
</tr>
</tbody>
</table>
Furthermore, cane trash dry matter yield is about 10 ton per 100 ton of fresh cane yield (Robertson & Thorburn, 2007). As mentioned before, 70% of this trash is burned resulting in nitrogen losses. More than 70% of the nitrogen is lost to the atmosphere through this process (Mitchell, Thorburn & Larsen, 2000). Therefore, if cane trash is burned, 23 kg N / ha / year of the 33 kg N / ha / year in residues is lost directly. Loss of N from cane harvest is about 65 kg N / ha / year. Consequently, on average there is a direct loss from the soil of around 81 kg N / ha / year.

A study from Boddey, Polidoro, Resende, Alves and Urquiaga (2001) showed that, in nine of 11 sites in Brazil studied, BNF input was significant and ranging from 25 to 60% of N assimilated of which the average of the results was just above 35%, which equals 34 kg N / ha / year.

Therefore, it can be concluded that an application rate of 60 kg N / ha / year is probably more or less sufficient to maintain nitrogen levels in the long-term, especially if trash burning is phased out (Figure 5.3). In other regions, for example Australia, much higher fertilizer rates in between 150 and 300 kg N / ha for sugarcane are very common (Keating, Verburg, Huth, & Robertson, 1997), which is 125-250 kg N / ha / year over a full cycle of 5 harvests and considerably larger than the 60 kg N / ha / year in Brazil as indicated by Macedo, et al. (2008). In this study Brazil is used as a reference case for sugarcane, while higher yields and application rates will be used for establishing ranges.

![Figure 5.3 - Overview of soil nitrogen balance for sugarcane cultivation](image)

### 5.5. Timber crop yields and nitrogen requirement

There are many wood crops suitable for energy purposes. Commonly used wood energy crops (Table 5.8) are willow, poplar and miscanthus in temperate regions, while Eucalyptus is a suitable energy wood crop for the tropics. In this paragraph cultivation of these several wood crops will be discussed.

Current recommendation of nitrogen application is 100 kg N / ha once every rotation (3 years) (Abrahamson, Volk, Kopp, White, & Ballard, 2002) and thus equals 30.4 kg N / ha / year. Adler et al. (2007) use a poplar yield of 8.9 odt / ha / year, which is almost equal to the willow yield used by Styles and Jones (2008). N Fertilization of 84 kg N / ha was carried out 4 times during a 10 year cycle, resulting in an average rate of 33.6 kg N / ha / year. The nitrogen content of dry willow biomass is 0.45% (Heller, et al., 2004).
Therefore around 40.5 kg N / ha / year is removed from the field. This is slightly higher than the rate of fertilization, which results in a net loss of 23.5 kg N / ha / year using a fertilization loss of 50% (S. Nonhebel, personal communication, June 13, 2008). Nitrogen deposition rates however, will, depending on location, bring the balance close to zero (Figure 5.4), especially in Europe, large parts of the USA and near the densely populated areas in Asia (Galloway & Cowling, 2002).

Table 5.8 - Timber cultivation yields

<table>
<thead>
<tr>
<th>Yield (odt/ha)</th>
<th>Crop</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Willow (U.S. commercial)</td>
<td>Keoleian &amp; Volk, 2005</td>
</tr>
<tr>
<td>4</td>
<td>Willow (Sweden commercial)</td>
<td>Keoleian &amp; Volk, 2005</td>
</tr>
<tr>
<td>11.9</td>
<td>Best willow clones</td>
<td>Keoleian &amp; Volk, 2005</td>
</tr>
<tr>
<td>2-44</td>
<td>Miscanthus (total range)</td>
<td>Lewandowski et al. (2000)</td>
</tr>
<tr>
<td>25</td>
<td>Miscanthus (European experiments)</td>
<td>Lewandowski et al. (2000)</td>
</tr>
<tr>
<td>11.7</td>
<td>Miscanthus (Ireland)</td>
<td>Styles and Jones (2008)</td>
</tr>
<tr>
<td>10-13</td>
<td>Eucalyptus (Nicaragua)</td>
<td>van den Broek, Vleeshouwers, Hoogwijk, van Wijk, &amp; Turkenburg et al. (2001)</td>
</tr>
<tr>
<td>16</td>
<td>Eucalyptus (experimental)</td>
<td>Sims, Senelwa, Maiava, &amp; Bullock (1999)</td>
</tr>
<tr>
<td>8.9</td>
<td>Poplar</td>
<td>Adler et al., 2007</td>
</tr>
<tr>
<td><strong>8.5</strong></td>
<td>United States</td>
<td><strong>Used in this study</strong></td>
</tr>
</tbody>
</table>

Binkley, Kaye, Barry, & Ryan (2004) state that for Eucalyptus in a medium fertilization treatment 700 kg N is added over a 8-year rotation, which equals 87.5 kg N / ha / year. This is comparable to miscanthus cultivation (Styles & Jones, 2008).

In this study an average yield of 10 ton / ha / year is used. This is similar to the yields of willow and poplar systems on which the energy and GHG balances will be based. The other yields and application rates will be used to establish ranges.

Figure 5.4 - Overview of soil nitrogen balance for willow cultivation
5.6. Wheat yields and nitrogen requirement

Table 5.9 - Wheat cultivation yields

<table>
<thead>
<tr>
<th>Yield (odt/ha)</th>
<th>Region</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>World 2000-2004</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>2.6</td>
<td>Asia</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>2.8</td>
<td>United States</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>8.4</td>
<td>Netherlands</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>7.7</td>
<td>United Kingdom</td>
<td>FAO, 2004</td>
</tr>
<tr>
<td>8.6</td>
<td>Europe</td>
<td>Used in this study</td>
</tr>
</tbody>
</table>

Wheat yields differ highly for different regions (Table 5.9). Nitrogen application rates vary widely. According to Velthof and Kuikman (2000), nitrogen content of wheat is 20 g N / kg wheat. In the Netherlands nitrogen application rates higher than 200 N / ha / year are common (Boerderij.nl, 2008). A life cycle study for wheat based ethanol by Punter et al. (2004) uses a nitrogen application rate of 185 kg N / ha / year for a yield of 8.6 ton / ha / year if all straw is plowed back. Here, the application rate is equal to the nitrogen removal. Considering that also nitrogen losses will occur, the actual average yearly application rate should be higher. In this study a N-application rate of 225 kg N / ha / year, since the GHG balance is based on a high yield and 185 kg N / ha / year appears to be insufficient. For this situation the nitrogen balance is as shown in Figure 5.5.

![Figure 5.5 - Overview of soil nitrogen balance for wheat cultivation](image)

5.7. Comparison of the cultivation of different energy crops

Contrary to the low conversion ratio from sugarcane to ethanol compared to other crops, the agricultural yield of sugarcane is much higher than the yield of the other crops. Rapeseed has the lowest yield, but the highest nitrogen demand. This suggests that rapeseed biodiesel per kg fuel needs large amounts of nitrogen input. Corn production also requires large amounts of nitrogen compared to timber and sugarcane. The latter two are much more efficient in converting nitrogen into biomass. Now that nitrogen input, agricultural yields and conversion ratios to biofuels are known, the next chapter will analyze the energy input and GHG emissions over the whole production lifecycle.
6. ENERGY AND GHG BALANCES OF BIOFUELS

In chapters 4 and 5 the lifecycle and agricultural cultivation have been described. From these results it is possible to obtain biofuel yields related to nitrogen input. Since the two main purposes of biofuels are delivering energy to transportation and reducing GHG emissions, energy input and GHG emissions over the whole lifecycle still need to be described. In this chapter the energy and GHG balances will be described such that the balances of the energy crops can be compared with one another.

6.1. Method

For the whole analysis of the required nitrogen for biofuels it is necessary to know how much nitrogen input is necessary to deliver a certain amount of renewable energy to transportation or to reduce a certain amount of GHG emissions. Therefore, in this chapter for each cropping system first the energy balance is described and a net output in MJ per kg of fuel will be calculated. This is done by subtracting the energy output of 1 kg of fuel by the required amount of energy to produce 1 kg of fuel. This balance is less complex than a greenhouse gas balance, since it is solely a balance of energy in- and outputs. The GHG balance, however, is partly based upon the energy balances, but also includes other non-energy related emissions. Because of the higher uncertainty in the GHG balances, more studies are compared to come up with the final values. Carbon soil emissions are not included in this study, since the uncertainty and variation of such numbers are too high. The output of GHG balance will be in the form of a reduction of kg CO$_2$-eq per kg fuel. This is done by subtracting GHG emissions over the whole lifecycle from the avoided emissions by using a biofuel instead of a conventional fuel. More details of how the balances are built up can be found in Appendix A. In the end both net energy output and GHG reductions can be compared among different fuels. Moreover, it can be concluded which fuel is most efficient in using energy input to deliver energy to transportation and which fuel reduce the largest amount of GHG emissions per kg fuel. Later on, this can be related to the nitrogen input to compare the various fuels on their nitrogen requirement for delivering net output and reducing GHG emissions.

6.2. Rapeseed biodiesel

6.2.1. Energy balances

Energy inputs are needed during both agriculture and conversion processes. Reijnders and Huijbrechts (2008) state that the cumulative energy demand (CED), which is the total energy demand of the full life cycle, for biodiesel from rapeseed is approximately 60% of the output. This is based on a study of Zah et al. (2007), who have carried out analyses for both the Swiss and European rapeseed system, of which the CED is respectively about 57.5% and 62.5%. In this study I use 60% as an average, while 57.5% is used as the lower end of the range. It is also stated in the study of Zah et al. (2007) that the CED of diesel is 90% as in their study every fuel is compared to gasoline (100%). Since biodiesel replaces diesel and not gasoline I use a CED of 69.4% as the higher end of the range.

The CED values mentioned above can be converted to net output in MJ per kg biodiesel. The energy content of biodiesel is about 17% lower than conventional diesel on a weight basis (DeOliviera, Quirinoi, Suarez & Prado, 2006). The energy content of conventional diesel is about 43 MJ / kg (Frondel, 2006). Based on these values the net output of rapeseed biodiesel is calculated and shown in Table 6.1.

<table>
<thead>
<tr>
<th>Derived from</th>
<th>Low end of the range</th>
<th>High end of the range</th>
<th>Used in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net energy output MJ / kg</td>
<td>10.9</td>
<td>15.2</td>
<td>14.3</td>
</tr>
<tr>
<td>GHG reduction CO$_2$-eq / kg biodiesel</td>
<td>-2.05</td>
<td>0.95</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Table 6.1 - Net energy output and GHG reduction per kg of rapeseed biodiesel

Zah et al., 2007; Reijnders & Huijbrechts, 2008
6.1.2. GHG balances

The greenhouse gas balance used in this study is based on the study from Reijnders and Huijbrechts (2008). They start their analysis with GHG emissions during cultivation in which they include carbon soil emissions and \( \text{N}_2\text{O} \) emissions. The former is not included in this study (Appendix A) and will, therefore, not be taken into account. The use emissions per MJ of diesel for all energy input during production.

The reduction per kg fuel is depicted in Table 6.1. It can be seen that the low end of the range even results in a GHG enhancement rather than a reduction. The value used in this study is a slight reduction, the number is more positive than that of Reijnders and Huijbrechts (2008), but mainly due to exclusion of carbon soil emissions.

6.3. Corn ethanol

6.3.1. Energy balance

Table 6.2 - Net energy output and GHG reduction per kg of corn ethanol

<table>
<thead>
<tr>
<th>Net energy output M( \text{J} / \text{kg} )</th>
<th>GHG reduction (kg ( \text{CO}_2\text{-eq} / \text{kg fuel} )</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,35</td>
<td>Oliveira et al., 2005</td>
<td></td>
</tr>
<tr>
<td>0,64</td>
<td>Kim and Dale, 2005</td>
<td></td>
</tr>
<tr>
<td>Low end of the range 2,4</td>
<td>-1,48</td>
<td>Own calculations; method Reijnders and Huijbrechts, 2008; Oliveira et al., 2005</td>
</tr>
<tr>
<td>High end of the range 6,8</td>
<td>1,3</td>
<td>Kim and Dale, 2008</td>
</tr>
<tr>
<td>Used in this study 5,4</td>
<td>0,35</td>
<td>Farrell et al., 2006; Hill, Nelson, Tilman, Polasky &amp; Tiffany, 2006</td>
</tr>
</tbody>
</table>

Multiple studies have been done to the energy balance of corn ethanol (Table 6.2). Compared to the energy content of ethanol corn has a low net output. Energy output/input ratios are in the range of only 1,1-1,4.

6.3.2. GHG balance

The GHG balances found in literature are presented in Table 6.2. The low end of the range shows a negative reduction as was the case with rapeseed. This is, however, the most extreme case. The value used in this study results in a low reduction.

6.3.3. Corn stover energy balances:

Sheehan et al. (2004) and Kim and Dale (2005) have calculated energy balances for corn stover ethanol. Some adjustments again have been made, yielding the following results (Table 6.3). The net energy output per kg biofuel is higher than the energy content of ethanol, since there is a surplus of electricity generated in the production process.

Table 6.3 - Net energy output and GHG reduction per kg of corn stover ethanol

<table>
<thead>
<tr>
<th>Net energy output M( \text{J} / \text{kg} )</th>
<th>GHG reduction (kg ( \text{CO}_2\text{-eq} / \text{kg fuel} )</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,10</td>
<td>Spatari, et al., 2005</td>
<td></td>
</tr>
<tr>
<td>30,9</td>
<td>2,65</td>
<td>Kim and Dale, 2005</td>
</tr>
<tr>
<td>Used in this study 27,4</td>
<td>2,66</td>
<td>Sheehan et al., 2004</td>
</tr>
</tbody>
</table>
6.3.4. Corn stover GHG balances

Results of GHG studies to corn stover are summarized in Table 6.3. The last value derived from Sheehan et al. (2004) is used in this study. It can be seen that due to a surplus of electricity the reduction per kg fuel is higher than the avoidance of GHG emissions from gasoline, which is 2.52 kg CO$_2$-eq per kg biofuel (Farrell et al., 2006).

6.4. Sugarcane ethanol

6.4.1. Energy balance

<table>
<thead>
<tr>
<th>Derived from/Source</th>
<th>Net output MJ / kg</th>
<th>GHG reduction (kg CO$_2$-eq / kg fuel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8+</td>
<td>Own calculations; method Reijnders and Huijbrechts, 2008; Macedo et al., 2008</td>
<td></td>
</tr>
<tr>
<td>2.35</td>
<td>Own calculations; method Reijnders and Huijbrechts, 2008; Macedo et al., 2008</td>
<td></td>
</tr>
<tr>
<td>Low end of the range</td>
<td>19.4</td>
<td>1.29</td>
</tr>
<tr>
<td>High end of the range</td>
<td>37.2</td>
<td>3.20</td>
</tr>
<tr>
<td>Used in this study</td>
<td>27.7</td>
<td>2.31</td>
</tr>
</tbody>
</table>

Table 6.4 - Net energy output and GHG reduction per kg of sugarcane ethanol

The net output for sugarcane ethanol is shown in Table 6.4. Most studies show an output higher than the energy content of ethanol due to the surplus electricity and heat generated. The high end of the range is a future scenario by Macedo et al. (2008), their basic scenario is used in this study.

6.4.2. Greenhouse-gas balance

All greenhouse gas balances presented in Table 6.4 and are built up in the same manner. Important to note is that also the methane and N$_2$O emissions from sugarcane trash burning are incorporated. The high reduction calculated by Blottnitz & Curran (2007) is clearly too high, since they show a higher energy yield per ha than obtained if the highest yield found (100 ton/ha), the highest conversion rate and the high heating value (HHV) of ethanol are used. The value based on the same scenario as the energy balance is used in this study.

6.5. Timber ethanol and electricity

6.5.1. Energy balances

<table>
<thead>
<tr>
<th>Derived from/Source</th>
<th>Net energy output MJ / kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.7</td>
<td>Adler et al. (2007)</td>
</tr>
<tr>
<td>Low end of the range</td>
<td>25.0</td>
</tr>
<tr>
<td>High end of the range</td>
<td>29.8</td>
</tr>
<tr>
<td>Used in this study</td>
<td>27.6</td>
</tr>
</tbody>
</table>

Table 6.5 - Net energy output per kg of timber ethanol

Heller et al. (2004) calculated an output/input energy ratio for the generation of willow electricity, which is 12.9. This results in an energy input of 279 MJ / MWh$_e$. The energy efficiency of the gasifier is 36% energy and the energy content of willow is 19.8 MJ / kg. This results in a total energy input of 0.55 MJ per kg of willow. For ethanol production from timber, the amount of surplus electricity generated from the lignin part is 4% on energy of the feedstock, which equals 0.79 MJ$_e$ / kg willow. According to Adler et al. (2007) and Faaij
(2006) around 8,12 MJ / kg willow is converted to ethanol. This results in net energy output of 8,36 MJ per kg willow and equals a net output of 27,59 MJ / kg ethanol. I use this as an average net output. The high end of the range is based on a future scenario of Faaij (2006), while the lower end of the range is calculated by assuming no surplus of electricity generated.

6.5.2. GHG balances

Table 6.6 - GHG reduction per kg of timber ethanol

<table>
<thead>
<tr>
<th>GHG reduction (kg CO₂-eq / kg fuel)</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low end of the range</td>
<td>1.29</td>
</tr>
<tr>
<td>High end of the range</td>
<td>3.19</td>
</tr>
<tr>
<td>Used in this study</td>
<td>2.87</td>
</tr>
</tbody>
</table>

The most simple willow energy route is generating electricity from it. This can best be done by a gasifier as clarified earlier. Heller et al. (2004) estimate a reduction of about 950 kg CO₂-eq per MWhₑ. For ethanol the GHG reductions are shown in Table 6.6. As was the case with the energy balances the low and high end of the range are respectively based on no electricity production and a future scenario.

![Figure 6.1 - Net energy output for different energy cropping systems](image-url)
6.6. Energy and GHG credits for byproducts

6.6.1. Energy and GHG balances for wheat

<table>
<thead>
<tr>
<th></th>
<th>GHG emissions (kg CO$_2$-eq / kg wheat)</th>
<th>Derived from/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
<td>0.307</td>
<td>Kramer, Moll &amp; Nonhebel (1999)</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>0.399</td>
<td>Kramer, Moll &amp; Nonhebel (1999)</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.238</td>
<td>Mortimer, Elsayed &amp; Horne (2004)</td>
</tr>
<tr>
<td>Wheat if straw removed</td>
<td>0.513</td>
<td>Punther et al. (2004)</td>
</tr>
<tr>
<td>Wheat if straw ploughed back</td>
<td>0.389</td>
<td>Punther et al. (2004)</td>
</tr>
</tbody>
</table>

GHG emissions for wheat production are presented in Table 6.7. In this study the value of 0.389 kg CO$_2$-eq per kg crop (Punther et al., 2004) is used. Transportation is not included, but also the byproduct of ethanol production has to be transported. This value is chosen for several reasons. It is based on a system in which straw is plowed back. If straw is removed and also fed to animals this positively influences the GHG of wheat, but also requires more agricultural inputs and maybe this results in more soil emissions. On the one hand this simplifies the upstream system, on the other hand straw is dealt with to some extent. Therefore, this is system is used. The energy balance will be obtained from the same study (Punter et al., 2004) of which the energy input amounts to 2.05 GJ per ton fresh wheat.

6.5.2. Rapeseed

The EW-value of rapeseed cake is 0.72 (Duynie, 2007). On average 57% mass of the rapeseed yield is converted to rapeseed cake, which means 1.7 ton / ha. The EW-value of wheat is 1.11, resulting in a wheat displacement of 1.1 ton / ha. This results in an energy and GHG reduction as shown in Table 6.8.

<table>
<thead>
<tr>
<th></th>
<th>Energy credit MJ / kg fuel</th>
<th>GHG credit kg CO$_2$-eq / kg fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed cake</td>
<td>1.8</td>
<td>0.35</td>
</tr>
<tr>
<td>Corn DDGS</td>
<td>1.55</td>
<td>0.29</td>
</tr>
</tbody>
</table>

6.5.3. Corn

DDGS has an EW-value of 0.82 (Duynie, 2006) per kg dry matter. From 1 kg corn 0.33 kg DDGS is produced, which is amounts to 2.81 ton / ha. This results in a substitution of wheat of 2.07 ton / ha, which results in the energy and GHG credit shown in Table 6.8.
6.7. **Comparison of energy and GHG balances of biofuels**

From Figure 6.1. can be seen that sugarcane and timber derived ethanol has a relatively much higher net output. That is, there is much less energy needed to produce ethanol from those two crops than energy needed to produce fuel from corn and rapeseed. Rapeseed biodiesel has a higher net output per kg than corn ethanol, but it should be noted that one kg of biodiesel also has a higher energy content than ethanol. Including the energy credits for rapeseed biodiesel and corn ethanol and including corn stover ethanol, shows a slightly more positive picture. However, sugarcane and timber still have much more favorable energy balances. Corn stover ethanol alone has favorable balances comparable to sugarcane and timber. Almost an equal picture can be drawn for the GHG balances (Figure 6.2.). Sugarcane shows a high reduction and timber ethanol even higher, while corn and rapeseed biofuels result in only minor GHG emission reductions. Therefore, it can be concluded that from an energy and GHG perspective sugarcane and timber ethanol largely outperform the other two biofuel routes. Now that the energy and GHG balances are known besides yields, conversion and nitrogen input, it is possible to link net output and GHG reduction to nitrogen input. This will be done in the next chapter.
7. NITROGEN RELATION WITH ENERGY AND GHG EMISSIONS

The preceding chapter has completed the data needed to directly link nitrogen input to net output and GHG reduction. Therefore, in this chapter the amount of energy and GHG reduction per extra kg nitrogen input for all different crops will be calculated.

7.1. Method
To establish the intended relation between nitrogen input and net output or GHG reduction, the results of the previous three chapters need to be combined. In order to calculate the net output and GHG reduction per extra kg nitrogen input, the following steps are carried out. At first, the agricultural yield per kg nitrogen output must be calculated. Next, using the conversion ratios mentioned in chapter 4, the biofuel yield per kg nitrogen is calculated. This again can be converted to net output or GHG reduction per kg nitrogen by multiplying this number by the results presented in chapter 6. At the end of chapter all crops can be compared by their efficiency of converting nitrogen input to net output and GHG emission reduction. This enables the calculation of nitrogen needed to attain a certain amount of output or GHG reduction.

7.2. Nitrogen vs. net output and GHG emissions for simple systems

Table 7.1 - Net outputs and GHG reductions for different biofuels

<table>
<thead>
<tr>
<th>Biofuel</th>
<th>Net energy output (MJ/kg N)</th>
<th>GHG reduction (kg CO₂-eq per kg N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed diesel</td>
<td>107</td>
<td>3,6</td>
</tr>
<tr>
<td>Corn ethanol</td>
<td>93</td>
<td>6,1</td>
</tr>
<tr>
<td>Sugarcane ethanol</td>
<td>2386</td>
<td>202,6</td>
</tr>
<tr>
<td>Timber ethanol</td>
<td>2425</td>
<td>252,4</td>
</tr>
<tr>
<td>Timber electricity</td>
<td></td>
<td>545,0</td>
</tr>
</tbody>
</table>

7.2.1. Rapeseed ethanol
Nitrogen application is for rapeseed is on average 165 kg N / ha. The average yield is 3 ton / ha / year, while conversion to biodiesel is 41.4 %mass. Net energy output and GHG reduction per kg biodiesel are respectively 14.3 MJ and 0.48 kg CO₂-eq. Overall this results in a net energy output and GHG reduction per kg N-input of 107 MJ and 3.6 kg CO₂-eq respectively (Table 7.1).

7.2.2. Corn ethanol
157 kg N is applied yearly per ha in the corn system, resulting in yields of 8.5 ton / ha / year. Conversion to ethanol is 0.322 %mass. Since the net output is 5.36 MJ and GHG reduction is 0.35 CO₂-eq per kg ethanol, the output and reduction per kg N applied are respectively 93 MJ and 6.1 kg CO₂-eq (Table 7.1).

7.2.3. Sugarcane ethanol
Application rates for sugarcane are on average 60 kg N / ha / year and yields are 72.5 ton / ha / year. From one ton cane 72.6 kg ethanol can be produced. The net energy output for ethanol is 27.7 MJ / kg ethanol and 2386 MJ per kg N. The reduction in GHG emissions is 2,31 kg CO₂-eq per kg, resulting in a reduction of 202,6 kg CO₂-eq per kg N applied (Table 7.1).

7.2.4. Timber ethanol
As average yield for timber crops 10 ton / ha is used with an application rate of 33.6 kg N / ha / year. Conversion rate to ethanol is 41 %energy, which is equal to 29.5 %mass for poplar. The net output per kg timber ethanol is 27.59 MJ / kg, which results in an output of 2425 MJ / kg N.
The GHG reduction is 2.87 kg per kg ethanol, which is equal to 252.4 kg CO$_2$-eq per kg N (Table 7.1).

7.2.5. *Timber electricity*

Because it is difficult to compare electrical energy with energy in ethanol, only the GHG reduction for timber electricity is calculated. Naturally the same yields and application rates are used, while conversion is different, 36\% energy. The GHG reduction is 948.8 kg CO$_2$ per MWh$_e$. Consequently, the GHG reduction is 545 kg CO$_2$ per kg N (Table 7.2.1).

![Figure 7.1 - Net energy output related to nitrogen input for different biofuels](image)

7.3. **Nitrogen vs. net output and GHG emissions for advanced systems**

Next, the systems for which it is possible will be optimized by giving credits for side-products and using agricultural residues if possible.

<table>
<thead>
<tr>
<th>Table 7.2 - Net outputs and GHG reductions of advanced systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net output (MJ / kg fuel)</strong></td>
</tr>
<tr>
<td>Rapeseed diesel</td>
</tr>
<tr>
<td>Rapeseed diesel + credit</td>
</tr>
<tr>
<td>Corn ethanol</td>
</tr>
<tr>
<td>Corn ethanol + credit</td>
</tr>
<tr>
<td>Corn + stover ethanol + credit</td>
</tr>
</tbody>
</table>

7.3.1. **Rapeseed**

As stated before, the production of biodiesel from rapeseed also results in a byproduct which can be fed to livestock. Incorporating an energy, a GHG and a nitrogen credit for this system, will change the results. Adding the energy and GHG credit result in an output of 16.4 MJ and a reduction of 0.88 kg CO$_2$-eq per kg biodiesel. Nitrogen credit for 1.28 ton displaced wheat.
per ha is 36 kg N / ha. Using all these credits net output and GHG credit per kg N are 158 MJ and 8,5 kg CO₂-eq respectively (Table 7.2).

7.3.2. Corn
Adding a credit for DDGS to corn ethanol will yield the following results. The nitrogen credit for 2,07 ton wheat / ha is 58,3 kg N / ha. Adding the energy and GHG credit will increase output and reduction to 6,91 MJ and 0,65 kg CO₂-eq per kg ethanol respectively. Consequently, the output per kg N is 192 MJ and the reduction is 17,9 kg CO₂-eq per kg N (Table 7.3.1).
If corn stover is also removed and converted to ethanol output and reduction will increase further. The energy output of corn stover is 27,4 MJ / kg ethanol. Upon 40% stover removal, this is on average 12 MJ / kg ethanol. The GHG reduction of stover is 2,66 kg CO₂-eq per kg ethanol. Corn and corn stover ethanol combined results in a reduction of 1,15 kg CO₂-eq per kg ethanol. If 40% stover is to be removed, application rates have to increase to at least 183 kg N per ha per year. With the N-credit for DDGS, this is equal to 124 kg N / ha / year. Consequently, per kg N net output and GHG reduction are 353 MJ and 33,8 kg CO₂-eq per kg N respectively (Table 7.2).

![Figure 7.2 - GHG emission reduction related to nitrogen input for different biofuels](image)

7.4. Comparison of nitrogen requirement in different biofuel routes
The efficiency of converting nitrogen input to net output and GHG emission reduction differs highly for the different energy crops. Low yields, high nitrogen application rates and unfavorable energy and GHG balances result in a low output and reduction per kg N for rapeseed and corn derived biofuels. Sugarcane and timber on the other hand show an output and reduction 1 to 2 orders of magnitude higher. This is logical due to the higher yields, lower nitrogen inputs and much more favorable energy and GHG balances.
It can be concluded that if we are going to produce biofuels on a large scale, sugarcane and timber should be used instead of corn and rapeseed from a nitrogen perspective. Now the net output and GHG reduction per kg N are known, it is possible to calculate the total nitrogen input needed for meeting certain targets. This will be addressed in the next chapter.
8. N REQUIREMENT COMPARED TO NATURAL FLOWS

The previous chapter has linked nitrogen input to net output and GHG emissions. This data can be used to calculate the global extra N requirement in the future. In this chapter the net output and the GHG reduction per kg N will be linked to the world demand in 2030. It shows what extra nitrogen input is needed, if we either want to replace all our fossil fuels or if we want to reduce all our emissions in transportation.

8.1. Method

In order to evaluate the impact of producing biofuels to the nitrogen cycle, the extra N requirement needs to be calculated and compared to natural flows. The data from the previous chapter shows the relation between output and nitrogen input. The extra N requirements can now be calculated as follows. At first the projected fuel energy demand and GHG emissions in 2030 need to be known. Dividing these numbers by the values calculated in the previous chapter, results in the extra N needed to replace all fuels or reduce GHG emissions.

8.1. Fuel energy demand 2030

To calculate the nitrogen needed to replace all our fossil fuels for transportation in 2030, the global energy demand is needed. The world energy outlook 2006 by the International Energy Agency (IEA, 2006) has estimated energy demands in 2030. In their reference scenario they state that the demand for fossil fuels in transportation is 3111 MTOE. One TOE (Ton Oil Equivalent) is equal to 42 GJ, resulting in an energy demand of 1,3 EJ.

8.2. Extra N-input needed for replacing fossil fuels

The net output of rapeseed biodiesel per kg N is 107 MJ. Replacing all our fuels by biodiesel from rapeseed would require 1217 Tg N, which is more than 11 times as high as the natural flow by BNF. If all rapeseed cake can be fed to animals and thus wheat cultivation is avoided, the output rises to 158 MJ / kg N. In that case, the extra N needed would be 829 Tg, still more than 7 times as much as natural input.

Corn ethanol has a net output of 93 MJ / kg N. If corn ethanol would be used as net fuel we would need an extra 1398 Tg N, a factor 13 higher than natural input. As I have pointed out earlier, the corn ethanol system can be optimized by using DDGS as byproduct and stover as a feedstock for ethanol too. If DDGS can avoid wheat production, the output increases to 192 MJ / kg N, resulting in an requirement of 682 Tg N. This is more than 6 times the natural flux. Including also corn stover in the system would increase the output further to 353 MJ / kg N. This would decrease the extra N-input to 370 Tg N, which is still 3,5 times natural occurring BNF.

Per kg N used for sugarcane derived ethanol, 2386 MJ is replaced. If this is used as a substitute for all our fuels, 55 Tg N is needed. This is half of the global natural fixation.

The net output for timber ethanol is 2425 MJ / kg N. Replacing all fuels, this would result in an extra N-requirement of 54 Tg. This is, as was the case with sugarcane ethanol, 0,5 times the natural flux. All N requirements are shown in Figure 8.1.
8.3. GHG emissions fuels 2030

From an environmental perspective it is more interesting to see what will happen if we want to reduce GHG emissions by using biofuels instead of just replacing oil-based fuels. Two scenarios are considered. The first is the extra nitrogen needed if we consider biofuels as renewable fuel for the long term and want to eliminate all GHG emissions in transportation. The second scenario is less extreme and based on the current Kyoto Protocol target, so what if we want to set GHG emissions by transportation in 2030 to the level of 1990. Total GHG emissions in 1990 and 2030 are respectively estimated on 3758 Mt and and 7993 Mt CO$_2$-eq.

8.4. Extra N-input for reducing GHG emissions

GHG reduction by rapeseed diesel is 3,6 kg CO$_2$-eq per kg N. To reduce all emissions in 2030 we would need an extra N-input of 2213 Tg to reduce all emissions and 1173 Tg to maintain the levels of 1990. Respectively this is a factor 21 and 11 higher than natural input. Since the reduction by rapeseed diesel with a credit for rapeseed cake is 8,5 kg CO$_2$-eq per kg N, the N requirement would decrease if wheat is replaced by rapeseed cake. This, however, would only decrease the requirement to 943 Tg for scenario 1 and to 500 Tg for scenario 2, which is still respectively almost 9 and 5 times as high as BNF.

Corn ethanol reduces GHG emissions 6,2 kg CO$_2$-eq per kg N. For scenario 1 this would mean an N-input of 1299 Tg, a factor 12 higher than natural. For scenario 2 this is an input of 688 Tg N, more than a factor 6 of natural fixation. The credit for DDGS increases reduction to 17,9 kg CO$_2$-eq per kg N. This decreases global N-requirement to 445 Tg for scenario 1 and 236 Tg for scenario 2. Also including stover for ethanol production, would decrease N-inputs further to respectively 236 Tg and 125 Tg, which are still 1 to 2 times as much as the natural flux.

Ethanol from sugarcane has a reduction of 202,6 kg CO$_2$-eq per kg N. Global N requirements for scenario 1 and 2 would be 39 and 21 Tg respectively. These requirements are 0,4 and 0,2 times global natural input.

Using timber ethanol with a reduction of 253 kg CO$_2$-eq per kg N, would result in an extra 32 Tg N for scenario 1 and 17 Tg N for scenario 2. These are fractions of 0,3 and 0,16 of natural fixation respectively. For comparison if would like to reduce the same amount of emissions by generating electricity from timber would only require about half of the nitrogen,
respectively 15 Tg and 8 Tg. Figure 8.2 shows all N requirements for GHG reduction for all crops.

8.5. Comparison of global N requirements of different biofuels

From the previous chapter could be concluded that global nitrogen requirements of the different biofuels would be lower for sugarcane and timber based biofuels and higher for the others. This can also be clearly seen from Figure 8.1 and Figure 8.2. Timber and sugarcane ethanol can replace conventional fuels and reduce GHG emissions without adding more than another quantity of nitrogen equal to the natural fixation. The amount is still significant, though, 0.3-0.5 times the natural flow. Using any of the other two considered crops to produce biofuels, would have a substantial effect on the global nitrogen cycle.

![Figure 8.2 - Nitrogen demand for eliminating all GHG emissions from fuels](image-url)
9. DISCUSSION, CONCLUSION AND RECOMMENDATIONS

The previous chapter has calculated the nitrogen requirements for replacing our fuels with biofuels or reducing our GHG emissions from transportation. In this chapter main conclusions will be drawn based on the results. First, however, this chapter discusses limitations of this study and the uncertainty of the results. This will ensure that the conclusions drawn are correct. At the end, also some recommendations for further research will be given.

9.1. Discussion

Agricultural practice and yields vary highly around the world. There are many site-specific factors that will influence cultivation and, therefore, energy and GHG balances. In this research values have been based on actual numbers in regions where a lot of the crops are already cultivated for biofuel production. This on the hand decreases uncertainty, since analysis is based on actual data. On the other hand it might not be feasible to produce these crops elsewhere in the same manner. This should be taken into account when drawing conclusions from the results. It would be highly unlikely that one crop would solely dominate biofuel production. In every region another crop is the most efficient in terms of yields, economics, energy and emissions. The results from this research should, therefore, not be used as an argument to choose for a crop on a specific site. The results merely show what order of magnitude of nitrogen is needed and what impact would be if we would use these crops to replace our fuels.

Also land use issues are not incorporated in this study. It is possible that there is not enough land to replace all fuels by biofuels. This has not been addressed in this study, but this will not affect the conclusions drawn. The purpose of this research was merely to show whether nitrogen input for replacing fuels is significant compared to nitrogen used in food production and natural flows. Whether it is possible to realize this considering land limitations is another issue that might be worth researching.

For all crops in both energy and GHG balances there are a lot of uncertainties. N₂O emissions for example, are under heavy debate with people arguing (Crutzen, Mosier, Smith & Winiwarter (2007) these emissions are much higher than the values of IPCC (2006). Furthermore, different studies come up with different energy inputs, yields, conversion rates and so on. However, the sensitivity analysis, using the most extreme cases, shows that variation in data used would not change the results.

Energy cropping systems producing byproducts have been credited for these byproducts. It is debatable, though, whether it is realistic to assume that these byproducts would all end up in meat production. If all our fuels are to be replaced by biofuels it would be unlikely that all byproducts would be eaten by animals. Therefore, the energy output and the GHG reduction for cropping systems have been calculated with and without credit. Moreover, the credit has merely been calculated to show what difference this would make for the energy and GHG balances and for the nitrogen requirement.

In chapter 8 the nitrogen demand was calculated if all fuels were to be replaced by these biofuels. This replacement is done by using the net energy output per kg nitrogen. This is a rough estimate and should be seen as such. Whether it is possible to replace all these fuels with biofuels is beyond the scope of this research and therefore has not been taken into account. It shows, however, the order of magnitude of nitrogen that is needed if it would be possible to replace all fossil fuels with these biofuels.

For the GHG reduction scenario there are other complications. This scenario could never be realized, since not all GHG emissions are energy related. There are also emissions from soil, e.g. N₂O emissions. Therefore, if all fuels are replaced still GHGs are emitted. As with the fuel replacement scenario, this scenario merely shows what nitrogen input would be necessary if we want to reduce GHG emissions by that order of magnitude.
9.2. Conclusion
Three main conclusions can be drawn from this research. The first one is that from the energy cropping systems studied timber and sugarcane need the lowest nitrogen input for producing a certain amount of biofuels. Rapeseed and corn systems on the contrary have a high nitrogen requirement. The allocation of byproducts does not change that picture. Consequently, from a nitrogen perspective we should mainly use timber and sugarcane, if we are going to use one of these energy crops on a large global scale.
The second conclusion is that current energy cropping systems will ask for significant nitrogen inputs. Using sugarcane and timber to replace our fuels, still half of natural flows is needed beyond our nitrogen demand for food production. That is, biofuel production will have an impact on the nitrogen cycle in the same order of magnitude as agricultural production so far.
The third conclusion is that electricity from timber is far more efficient in reducing GHG emissions. Replacing all fuels with biofuels will have a significant impact on nitrogen cycle. This suggests that perhaps we should focus more on generating electricity rather than on producing biofuels.
All in all, producing biofuels will have a significant impact on the nitrogen cycle. The main idea behind biofuels is to reduce global warming potential. Many studies including this one have demonstrated that biofuels are not 100% energy and GHG neutral. Besides that, this study has shown that using biofuels to reduce global warming will only shift the environmental burden more towards the nitrogen cycle.

9.3. Recommendations
A few recommendations for future studies have already been made in the discussion. Here a few more will be pointed out.
Carbon soil emissions and N\textsubscript{2}O emissions still are highly uncertain factors. Therefore, it is hard to establish correct GHG balances. If emissions turn to be out much higher or lower than assumed until now, this might affect conclusions drawn from studies like this. Consequently, it will be necessary to be more certain of these factors and research is needed in that area.
In agriculture nitrogen needs are mainly fulfilled by using either manure or artificial fertilizers. However, there are plants like sugarcane which are able to fix nitrogen. If it would be possible to use nitrogen fixing bacteria in the cultivation of other plants, this might reduce our artificial nitrogen needs. Research on whether this is possible and the effects could be done in the future.
In current production systems most nitrogen is lost during production of biofuels. Maybe it would be possible to recycle much of the nitrogen in the conversion processes. If this would be possible, the rate of nitrogen fixation for biofuels would decrease dramatically.
At last, more sophisticated systems could also be subject to a nitrogen study. For example, what will be the impact of using agricultural residues, organic waste, algae or other sources. These systems might be superior in using nitrogen.
APPENDIX A – BUILD-UP OF ENERGY AND GHG BALANCES

As mentioned in chapter 6, all energy and GHG balances are built up in such a way that they can be compared. In this appendix the build of the energy and GHG balances is explained. To compare the energy balances and to calculate net output per kg fuel obviously all units are converted to standard units. Some studies present their results per ha of agriculture production, some per kg fuel, others per ton of agricultural product and so on. All these values have been converted to the energy related to the eventual output, 1 kg of biofuel. Besides unit conversion it is assured that each balance consists of energy used during all production stages. The total energy input over the whole chain is summed. Energy output by byproducts, such as electricity and heat, is subtracted. The result is then subtracted from the LHV of 1 kg of fuel in order to come up with the net output per kg fuel.

The GHG balances are based on emissions related to energy input during the lifecycle, but also non-energy related emissions from agriculture are taken into account where possible. Nitrous oxide emissions related to nitrogen fertilizer are the same in every GHG balance. The emission rate of N$_2$O is calculated by using a fertilizer conversion of 1,325 % on a N/N weight basis (IPCC, 2006). Some scientists argue that N$_2$O emissions are higher (Crutzen, et al., 2007), while also lower numbers can be found. Reijnders and Huijbrechts (2008) use a range of 1.5-5 %mass of the fixed nitrogen added to the field. Both extremes have been used for calculating the low and high end of the range. Appendix B shows the maximum ranges that can be calculated from values found in literature.

Also an increase or decrease in soil carbon would influence the GHG balances. Soil carbon is not included in this study, however, because of the high uncertainty. Different studies show very different numbers. Some argue that agriculture would result in soil carbon loss, while others state that below ground biomass sequesters carbon into the soil. Vleeshouwers and Verhagen (2002) estimate a carbon soil loss of 3,08 Mg CO$_2$ / ha / year, which is also used by Reijnders and Huijbrechts (2008) in their analysis. For sugarcane cultivation carbon soil loss is estimated to be 14,7 Mg CO$_2$ / ha / year and 2,5 Mg CO$_2$ / ha / year for 12-year and 50-year cultivation respectively by Vitorello (1989) and is 1,0 Mg CO$_2$ / ha / year for a 65-year cultivation according to Bashkin & Binkley (1998). On the other hand Adler et al. (2007) and Keioleian and Volk (2005) estimate carbon soil sequestering on the short-term for poplar cultivation and Kim and Dale (2008) and De Oliveira et al. (2005) do the same for corn-cultivation.

Apart from the carbon soil emissions itself the reference system is very hard to identify as well. That is, what will the land be used for if there would be no agriculture and what would soil emissions be in that case? Former land use is also a very important factor. What if the bioenergy cropping systems would replace a tropical forest? Reijnder and Huijbrechts (2008) estimate that for the replacement of a tropical forest would release 700 Mg CO$_2$ per ha. It would take 50 years to offset this using a sugarcane ethanol system. All in all it can be concluded that carbon soil emissions and former land use are dependent on too many site-specific factors and the uncertainty is so high that it would not be wise to include any loss or sequestration in this research. This does not mean, however, that carbon soil emissions are not important. More should be known on carbon soil emissions to establish a sound GHG balance for specific production sites as it can significantly influence the results for biofuels. For example, a carbon soil loss of 2,5 Mg CO$_2$ / ha / year (Vitorello, 1989) would result in an extra 0,5 kg CO$_2$-eq per kg ethanol for a high yielding crop as sugarcane. Moreover, this topic needs to subjected to more research in the future.
The GHG balances are, thus, built up in the same manner including nitrous oxide emissions and energy related emissions. Avoided energy byproducts such as electricity and heat are subtracted from the GHG balances. Therefore, a negative GHG balance is possible. In order to obtain a GHG reduction per kg biofuel, the GHG avoidance of using 1 kg biofuel instead of a conventional fuel containing an equivalent of combustion energy is subtracted from the lifecycle emissions per kg biofuel. For ethanol an avoidance of 2.52 kg CO$_2$-eq per kg biofuel (Farrell et al., 2006) is used, while for biodiesel 3.25 kg CO$_2$-eq per kg biodiesel (Frondel & Peters, 2006) is used. The same buildup of the energy balances reduces the risk of drawing wrong conclusions. Many numbers are uncertain, but using the same numbers for the same emission sources for the different crops reduces the overall uncertainty.
APPENDIX B – SENSITIVITY ANALYSIS

In this appendix extreme ranges are presented. This enables to check whether high variations would invalidate any conclusions drawn. The low and high end of the range are calculated by using all extreme values found in literature. For the low end of the range the most unfavorable values are used, while for the high end of the range the most favorable values are used.

In Figure B.1 the ranges in net output per kg fuel are shown. From this graph it can be seen that timber and sugarcane are still more favorable from an energy point of view even if the worst case is compared with the best case of the other crops. In Figure B.2. the same ranges are shown for GHG reduction. Here, the picture does not change as well.
The variation in the relation between nitrogen input and net energy output (Figure B.3) or GHG emission reduction (Figure B.4) is not that high as well. Only the positive variation in timber could change the picture of the nitrogen requirement in such a way that it would change the conclusions drawn. The most positive scenario is about 3 times as positive and would, therefore, decrease global N requirement by a factor 3. However, as is stated before the ranges presented here are the most extreme cases.
10. LITERATURE


Parton, W., Brenner, J., & Sheehan, J. (2002). The good news about ethanol production. In *18th Annual Clean Air Conference* Breckenridge, CO.


