



IEA Bioenergy
Technology Collaboration Programme

Nitrogen flows in biomass combustion systems

A parametric scoping study aimed at optimising nitrogen flows in biomass combustion

December 2022





IEA Bioenergy

Technology Collaboration Programme

Nitrogen flows in biomass combustion systems

A parametric scoping study aimed at optimising nitrogen flows in biomass combustion

J. Koppejan - ProBiomass BV

Christoph Schmidl - BEST Research

December 2022

Copyright © 2022 IEA Bioenergy. All rights Reserved

ISBN 979-12-80907-23-3

Published by IEA Bioenergy

Summary

The release of reactive nitrogen (Nr) in the form of ammonia (NH₃) and nitrogen oxides (NO_x) from a wide variety of sources in society such as combustion processes and agricultural activities rises concerns due to its direct and indirect (as precursor) harm to environment and public health. It negatively impacts ambient air quality and can lead to unwanted deposition of reactive nitrogen in nature conservation areas, the latter leading to unwanted shifts in vegetation type and disturbing eco-balances. This has led to several legal regulations aiming at reducing the release of reactive nitrogen to the environment (e.g., EU National Emission Ceilings NEC directive, emission limit regulations, and air quality rules).

For the thermal use of biomass intensive debates are ongoing on the level of emissions of NO_x at the stack, however only little research has been done on the quantification of reactive nitrogen flows along the whole biomass combustion cycle, including biomass growth and harvesting. It is important to address the system perspective here, since there is a fundamental difference between biomass combustion and other sources of reactive nitrogen like engines or fertilizers. While the NO_x emission from solid biomass combustion is typically only related to the nitrogen contained in the fuel and can never exceed that level in practice due to the relatively low combustion temperatures, NO_x emissions formed from fossil sources typically results in additional reactive nitrogen that was not in our ecosystem before. Biomass combustion can thus act as a net sink of reactive-nitrogen.

Results from an Austrian study on small-scale combustion systems show that approximately half of the nitrogen contained in wood fuels is emitted as NO_x while the other 50% are converted to harmless N₂. For other biomass types or combustion systems this may be different. As almost all tree species take up the nitrogen in form of reactive nitrogen species from the soil, the energetic wood use results in a net negative Nr balance. This mechanism however depends on various parameters, such as the type of biomass being used and its ability to absorb Nr, the possible use of fertilizer for some biomass types in the growth cycle, the performance of the deNO_x system in place and the possible release of ammonia slip, alternative uses for the residues, siting of a combustion plant in relation to nearby nature conservations areas, etc. Such factors should be taken into account when evaluating the possible impact of biomass combustion systems on Nr balances at a system level.

This scoping study aims to identify the key parameters that influence nitrogen balances for a broad diversity of biomass combustion plants based on different technologies and fuels with varying nitrogen contents. In a subsequent study to be carried out in 2022-2024, the influence of the mentioned parameters will be studied in more detail and quantified to provide policy recommendations for optimal use of various biomass combustion systems under various conditions.

Contents

Summary.....	1
1. Introduction	3
1.1 Formation and environmental effects of nitrogen species	3
1.2 NO _x emission from biomass combustion	4
2 Case studies	6
2.1 Case 1: Small scale combustion of woody biomass	6
2.2 Case 2: Forest residue removal for bioenergy.....	8
2.2.1 Biomass extraction removes nitrogen	8
2.2.2 Avoided nitrogen emissions in the reference system.....	9
2.3 Case 3: straw from winter wheat for combustion	10
3 Influencing parameters	11
3.1 Biomass species.....	11
3.2 Fertilizer application	11
3.3 NO _x emission of harvesting and transportation equipment	12
3.4 NO _x formation during end-use.....	12
3.5 Post combustion DeNO _x installations	14
3.6 Local nitrogen deposition rates influences plant type and nitrogen content.....	14
3.7 Siting of the combustion system	16
4 Conclusions and outlook	17
5 References.....	18

1. Introduction

1.1 FORMATION AND ENVIRONMENTAL EFFECTS OF NITROGEN SPECIES

In several countries world-wide, the emission of reactive nitrogen from various processes in society has become a significant environmental issue. In contrast to unarmful elemental nitrogen (N_2) that is present in abundance as the main component of the ambient air we breathe, reactive nitrogen species such as ammonia (NH_3) and nitrogen oxides (NO_x) are of increasing concern due to their negative effects on air quality and unwanted eutrophication of nature conservation areas.

In this respect, Ammonia (NH_3) is typically formed from animal husbandry and the use of NH_3 -based fertilizer applications, but it may also be released from industrial processes, vehicles and volatilization from soils and oceans. Ammonia is a gas that also contains reactive nitrogen, and therefore has similar effects on our ecosystem as NO_x .

Nitrogen oxides (NO_x) are oxidised forms of nitrous gases such as nitrous oxide (N_2O), nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Here, N_2O or laughing gas is formed mainly in cases of intensive agriculture, if there is insufficient oxygen available for full oxidation of nitrogen compounds. It is also a strong greenhouse gas (300 times the GHG warming effect of CO_2). As it is converted back to NO using ozone in the stratosphere, it also contributes to depletion of the ozone layer.

NO and NO_2 are formed and emitted during various combustion processes, such as happening in residential and industrial facilities and road transport. NO_x contributes to the formation of ozone and particulate matter (smog) and may thus deteriorate local air quality. Upon atmospheric chemical reactions, it may also be deposited as acid rain on nature conservation areas and thus lead to unwanted nitrogen enrichment or eutrophication.

The presence of additional reactive nitrogen from airborne ammonia has a direct toxic effect on slow-growing species such as lichens and mosses that originally live in our natural environment, leading to increased vulnerability to drought, frost damage and pests. Excess nitrogen also encourages the growth of nitrogen-loving species such as grasses and nettles, which are fast growing and which outcompete the original vegetation. In coastal areas, it may cause excessive growth of phytoplankton, microalgae (e.g., epiphytes and microphytes), and macroalgae (i.e., seaweed). These, in turn, can lead to other impacts such as loss of subaquatic vegetation, change in species composition, coral reef damage, low dissolved oxygen, and the formation of dead zones (oxygen-depleted waters) that can even lead to ecosystem collapse if nitrogen deposition becomes really severe. For every individual ecosystem, one can thus define a critical load as a quantitative estimate of exposure to reactive nitrogen (in mol/ha/year), above which significant harmful effects on specified sensitive elements of the environment may occur.

A summary of the European nitrogen flows for the year 2000 was published in the European Nitrogen Assessment [Sutton et al, 2011], see Figure 1. The figure illustrates that the largest emissions of reactive nitrogen to atmosphere originate from industry and traffic (3.4 Mton) and agriculture (3.8 Mton).

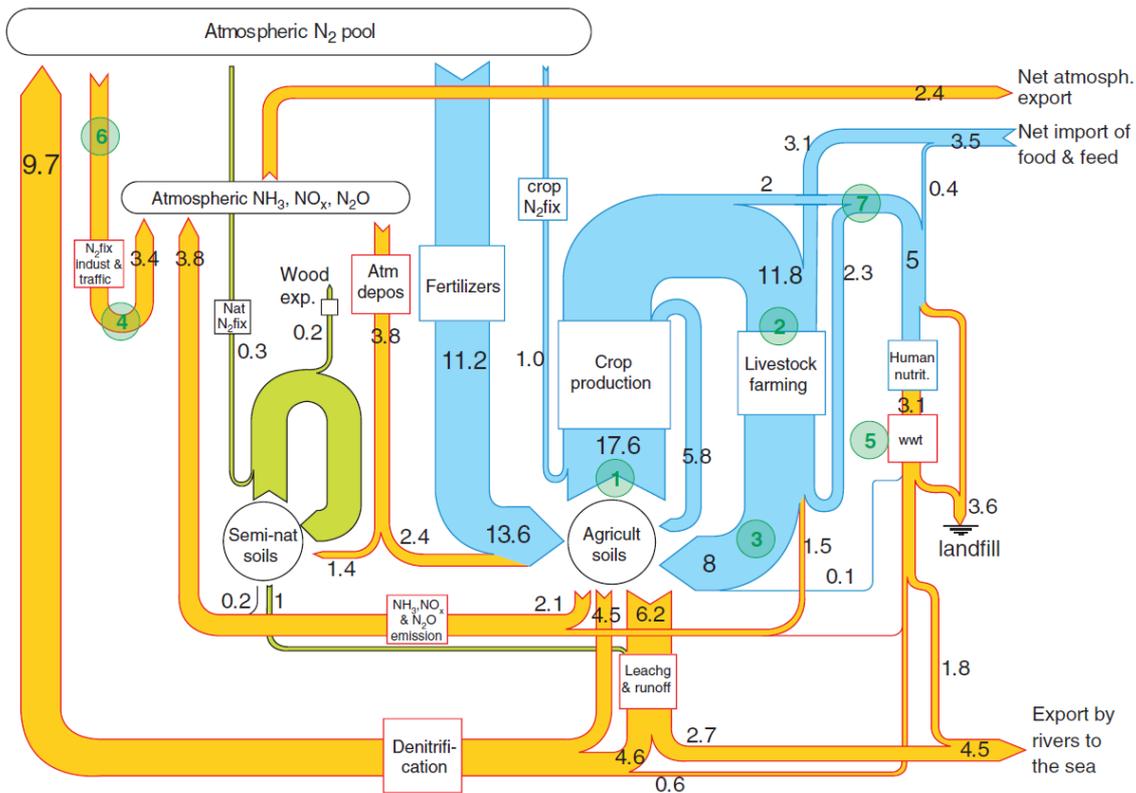


Figure 1 The N cycle at the scale of EU27 for the year 2000 [Sutton et al, 2011]. Numbers refer to fluxes in Mton N per year. Fluxes in green refer to ‘natural’ fluxes (to some extent altered by atmospheric Nr deposition), those in blue are intentional anthropogenic fluxes, those in orange are unintentional anthropogenic fluxes. The numbered green circles refer to recommendations given by the author to mitigate adverse impacts.

In order to mitigate their negative effects on ambient air quality, emission limits for NO_x and NH_3 are often imposed by national or regional authorities for various applications. Although this has led to a gradual reduction in these emissions over time, in Europe there were still 22 countries in 2019 (of which 18 were EU Member States) with registered ambient NO_x concentration levels above the EU annual limit value (the same as the 2005 WHO guideline).

European member countries also need to comply with their national emission ceilings. Although all EU member countries met their NEC ceiling for NO_x in 2020, there were still 11 countries that exceeded their NEC limit for NH_3 [European Environment Agency, 2022]. In addition, significantly lower NEC levels are imposed for 2030, therefore further effort is needed.

1.2 NO_x EMISSION FROM BIOMASS COMBUSTION

With regard to NO_x emission from combustion processes, there is a fundamental difference between combustion of fossil fuels and biomass fuels. During combustion of fossil fuels, NO_x is predominantly formed from oxidation of elemental nitrogen present in combustion air (N_2) due to relatively high combustion temperatures far above 1000°C . The so-called thermal NO_x leads to additional reactive nitrogen in the ecosystem. During combustion of solid biomass however, combustion temperatures are typically much lower than 1000°C and NO_x is predominantly or completely formed from oxidation of part of the nitrogen species that are already present in the biomass fuel. The amount NO_x formed from fuel nitrogen during the

combustion process depends on

- the amount of fuel nitrogen (more fuel nitrogen implies more NO_x)
- the amount of oxygen available to oxidize nitrogen species (more oxygen implies more NO_x)
- The necessity to increase temperature and oxygen to achieve full combustion of organic compounds and achieve low CO concentrations.

After the formation of NO_x , there are different methods (catalytic and non-catalytic) to reduce its emission in the flue gas. Overall and depending on the combustion and flue gas cleaning technologies used, no more than about 10-50% of the nitrogen contained in wood fuels is emitted as NO_x . As the fuel nitrogen species were originally formed during the growth of the plant or tree by capturing reactive nitrogen from the soil, the energetic use of this biomass results in a net negative N_r balance. This balance may be less favourable for nitrogen fixing species that are able to capture molecular nitrogen from the air, or if nitrogen containing fertilisers were applied to grow this biomass fuel, since these are formed from molecular nitrogen using the Haber Bosch process.

To illustrate the system perspective, three cases are presented hereafter.

2 Case studies

2.1 CASE 1: SMALL SCALE COMBUSTION OF WOODY BIOMASS

A recent study by Enigl et al. aimed at verifying the hypothesis that wood from sustainable forest management can act as a "nitrogen sink" because the nitrogen emitted by the combustion process was previously absorbed by the trees [Enigl et al., 2017]. The study analysed the impact of biomass-based domestic heating systems on the nitrogen cycle. This was represented in a simplified model, considering the path of nitrogen from forest, through firewood and its combustion to the emission of NO_x into the atmosphere.

The model was based on a sustainably managed (no forestry use) spruce forest in Höglwald, Germany. The forest is characterized by a high storage of nitrogen: 1500 kg N/ha in the biomass and 9000 kg N/ha in the soil. The annual nitrogen uptake through the trees is 100 kg/ha and the release is 90 kg/ha. The difference between uptake and release matches the N in the biomass increment ($5000 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ with 0.2 % N = 10 kg N).

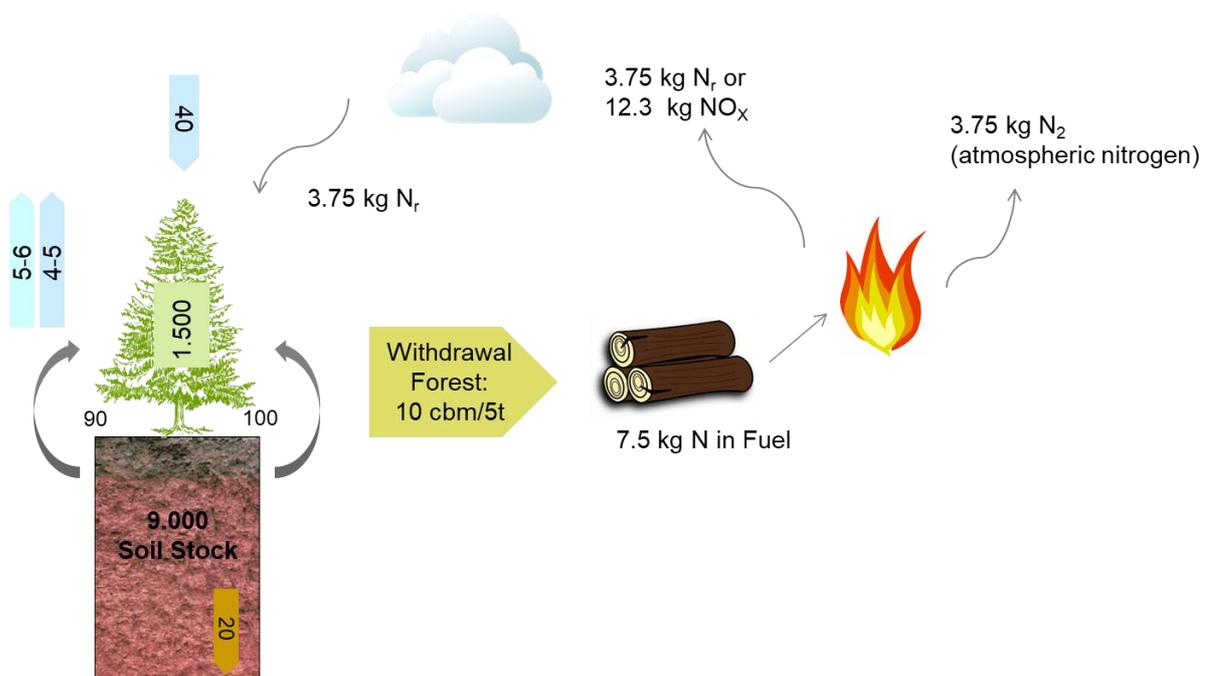


Figure 2: Model of N-cycle during biomass combustion based on a spruce forest in Germany. Amounts of nitrogen are referred to 1 hectare and 1 year. (Enigl et al., 2017) with elements from European Nitrogen Assessment, 2011)

The trees can only exploit a certain amount of nitrogen. Excess nitrogen deposited will be stored in the soil and leached once the soil has reached its capacity limit (saturation). In this particular case, the high nitrogen leaching ($20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$) indicates that the nitrogen input is more than what can be sustainably absorbed by the forest. Overall, the release of reactive nitrogen (N_r) from the forest is approx. $25 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$, of which $20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ leaches to groundwater and 4 - 5 $\text{kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ is released to the atmosphere).

The model included the following assumptions:

- The annual increment in the spruce forest (5t per hectare) is harvested and used for combustion (100 % energetic use, no material use)
- Average N-content in the wood: 1500 mg/kg db
- Wood is combusted in small-scale heating systems that do not involve any deNO_x technology
- 50 percent of the N-content in the wood is assumed to be converted and emitted as NO_x, the remaining 50 % in the form of molecular N. This assumption was based on own data of combustion tests available at BEST GmbH.

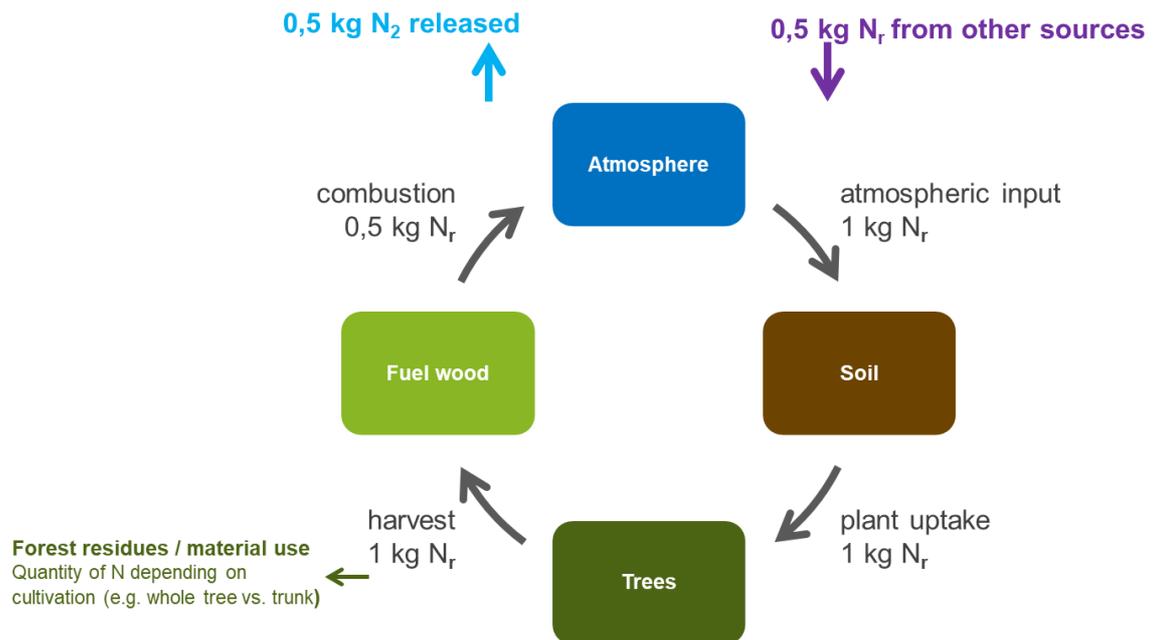


Figure 3: Simplified cycle of reactive nitrogen (Nr) in small-scale wood combustion. (Wopienka et al., 2018)

Model results showed that:

- Woody biomass takes up nitrogen from reactive N-compounds out of the soil that had been eluted from the atmosphere before.
- With the removal of wood from the forest, nitrogen is also removed. The amount of nitrogen contained in the wood ($7.5 \text{ kg*ha}^{-1}\text{*y}^{-1}$) is clearly below the amount of atmospheric nitrogen deposition ($40 \text{ kg*ha}^{-1}\text{*y}^{-1}$) and the amount of nitrogen leaching from the soil ($20 \text{ kg*ha}^{-1}\text{*y}^{-1}$).
- A completely energetic use in the assumed combustion systems results in a release of 50% the nitrogen contained in the fuel (approx. $4 \text{ kg*ha}^{-1}\text{*y}^{-1}$) as reactive nitrogen compounds (NO_x). This is in the same order of magnitude as the natural release of Nr from the forest to the atmosphere. The remaining $\text{kg*ha}^{-1}\text{*y}^{-1}$ of reactive nitrogen are taken out of the ecosystem as they are released as molecular N.
- In case the wood is partly used for material purposes (as is usually the case), the amount of nitrogen contained in the fuel, and consequently also the amount of NO_x released would be lower.

The study concluded that, in sustainably managed forests, the use of wood for energy recovery fulfils the function of forest as a "nitrogen sink". Furthermore, due to low combustion temperatures there is no or hardly any oxidation of combustion air nitrogen. Therefore, wood combustion does not add reactive Nitrogen compounds to the atmosphere.

As the N_r emitted during combustion was previously taken up by the tree, no additional N_r is introduced into the N cycle.

2.2 CASE 2: FOREST RESIDUE REMOVAL FOR BIOENERGY

2.2.1 Biomass extraction removes nitrogen

Plants and trees growing under natural conditions use reactive nitrogen to grow. In case of a tree, it is mostly stored in the branches and bark. In an unmanaged forest where no harvest takes place, these tree parts decay on the forest soil. In areas of high deposition where already saturated forest soils are common (such as in Central Western EU, see also Figure 10), the soil may leach the excess nitrogen. By harvesting the biomass residues however, this additional nitrogen load can be avoided, resulting in a reduced accumulation in and leaching from forest soils.

Callesen et.al. (2010) compared reactive nitrogen flows from unmanaged and managed forests in Suserup, Denmark, to assess the impact of wood harvesting for product and energy use on nitrogen flows. The forest soils concerned are nitrogen saturated with relatively high deposition and leaching. The results are summarised in Figure 4 and Figure 5.

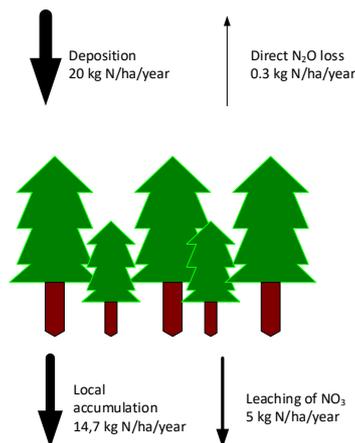


Figure 4 Nitrogen flows in unmanaged forest with high deposition and leaching. (Callesen et al, 2010)

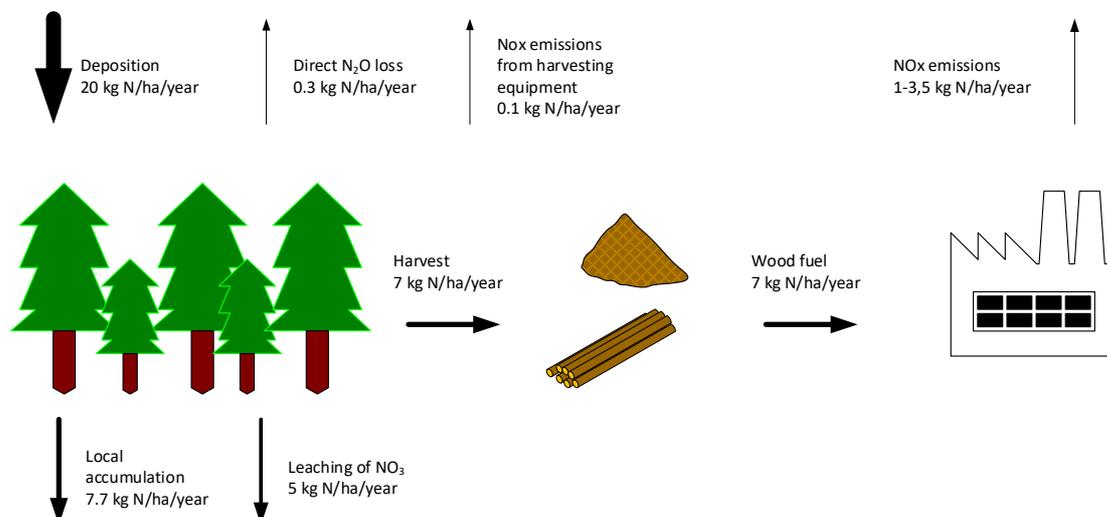


Figure 5 Nitrogen flows in managed forests with high deposition and leaching. (Callesen et al, 2010).

A comparison of both figures shows that the harvesting of wood from the forest indeed leads to an annual reduction of $7 \text{ kg*ha}^{-1}\text{y}^{-1}$ less local accumulation of reactive nitrogen in the soil, since the wood products and wood residues containing nitrogen are removed from the forest.

Since the nitrogen is mainly contained in the residue fraction as bark, approximately the same amount of nitrogen is also fed to the bioenergy plant. Depending on the type of combustion installation, only about 1-3.5 kg of the nitrogen is again released as NO_x , in addition to extra NO_x from combustion engines used in harvesting equipment and transport (0.1 kg). In total, the flow of reactive nitrogen input to the soil is reduced by approx. 3.4 - 5.9 $\text{kg kg*ha}^{-1}\text{y}^{-1}$. The 3.5 dry ton per ha harvested yield 68 GJ of wood fuel.

Similar to the example in case 1, this example shows that the accumulation of reactive nitrogen in the forest does not increase when reactive nitrogen is emitted as NO_x from burning wood residues from the area, as this emission is still significantly lower than the amount of nitrogen that is removed with the forest operations.

One additional aspect is the observation that with the removal of forest residues, reactive nitrogen is also directly removed from the forest. In case of already saturated soils, this may help to avoid unwanted eutrophication. Although a fraction of this may again be released during combustion, the amounts thus released are significantly lower than the amounts saved. Moreover, in case the combustion installation is located in another area that is less sensitive to eutrophication (further away from a nature conservation area) the effects may be less profound. Since stack level emissions are however higher than that of e.g. a natural gas fired boiler, it should be verified if the impact on local air concentration levels and the impact on deposition in other nature conservation areas can still be justified.

2.2.2 Avoided nitrogen emissions in the reference system

It should be noted that the above analysis by Callesen et.al. (2010) is limited to the direct effect of harvesting and using wood residues for energy. In principle it would be more appropriate to enlarge the system boundary and include a reference system for energy production in the analysis, in case it is assumed that the natural forest is left untouched. One can show that in case a natural gas fired boiler would be used to deliver the same amount of heat (58 GJ of heat per ha of forest) with a typical NO_x emission of $70 \text{ mg/m}^3@3\% \text{ O}_2$, this would result in 0,4 kg of N/year, which would then also be released to the ecosystem. The net benefit then increases to 3.8-6.3 kg of reactive nitrogen.

2.3 CASE 3: STRAW FROM WINTER WHEAT FOR COMBUSTION

It is common practise to apply nitrogen rich fertilisers to stimulate crop growth. For this purpose, ammonia or nitrate containing fertilisers are typically produced from molecular nitrogen present in air using the Haber Bosch process. This way, additional reactive nitrogen is added to the agricultural systems that was not there before. Excess N that is not picked up by the plants may leach from the saturated soil and affect the overall ecosystem.

Callesen et. al. also evaluates the case of growing winter wheat in Denmark, of which the straw by-product is used as a fuel. During growth, the use of fertilizers results in an input of 166 kg of N_r per ha, in addition to 1 ton of lime and pesticides. 130 kg of N is contained in the straw, chaff and grains, approximate distribution 20%, 15% and 65%, respectively (K. M. C. Fernando et. al, 2021). The production, harvesting and transportation requires various types of machinery.

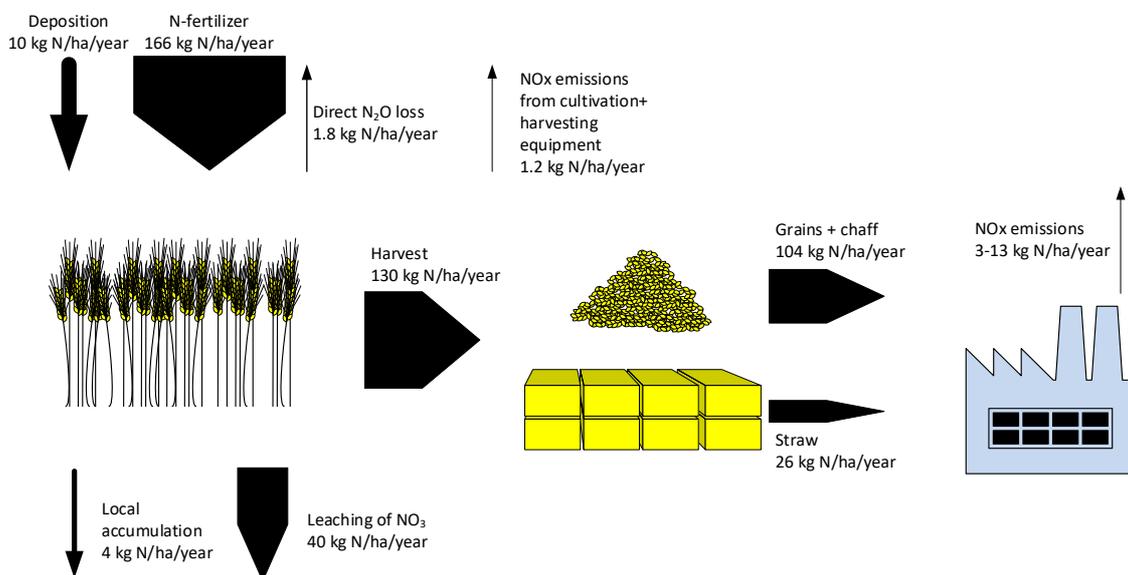


Figure 6 Nitrogen flows in growing winter wheat for energy. Derived from Callesen et al, 2010)

This system yields 12.5 dry tons of straw per ha, equivalent to 174 GJ of harvested straw, while the machinery and the production of fertilizer uses some 18 GJ (a net yield of 156 GJ). In the system described, 166 kg of reactive nitrogen is included in the form of N fertilizer. Approximately 15% (26 kg) of this reactive nitrogen is directed towards the fuel, and depending on the type of de-NO_x system applied some 3-13 kg N_r (2-8% of the input) is released in the form of NO_x.

A comparison of this system with the system for harvesting wood residues shows various differences, particularly:

The use of artificial N based fertilizer to the agricultural system results in increased leaching of nitrate (NO₃) to ground water, direct N₂O loss to the atmosphere and increased nitrogen fuel contents in both the biomass residues and the main crop. However, since in terms of economic value grains are the main crop and straw is considered a by-product, it can be questioned if the additional contribution of reactive nitrogen to the ecosystem should be attributed to the main crop (grains) or to the energetic use of straw. This also complicates a fair comparison between the wood-based and agroresidue-based bioenergy systems.

3 Influencing parameters

A thorough system analysis is needed to identify and understand the parameters that influence reactive nitrogen flows in specific bioenergy systems. Generally, one can distinguish a number of key influencing parameters for typical bioenergy supply chains, based on various types of biomass production, harvesting and conversion systems.

3.1 BIOMASS SPECIES

By far most of the plants and trees only use reactive nitrogen for their growth. In this case, it can be stated that all nitrogen contained in plant/tree material originates from reactive nitrogen that was absorbed during the growing phase. There are however a limited number of plants and trees that are capable of directly fixing molecular nitrogen from the air for their own purpose, and to add it to the soil with the help of bacteria. Examples of so-called nitrogen fixing species are Acacia, Robinia, Golden Chain tree, alfalfa, clover, beans, peanuts, and soybeans (annuals). In such cases, the harvested biomass may contain more nitrogen than what was added during the growing phase in the form of reactive nitrogen.

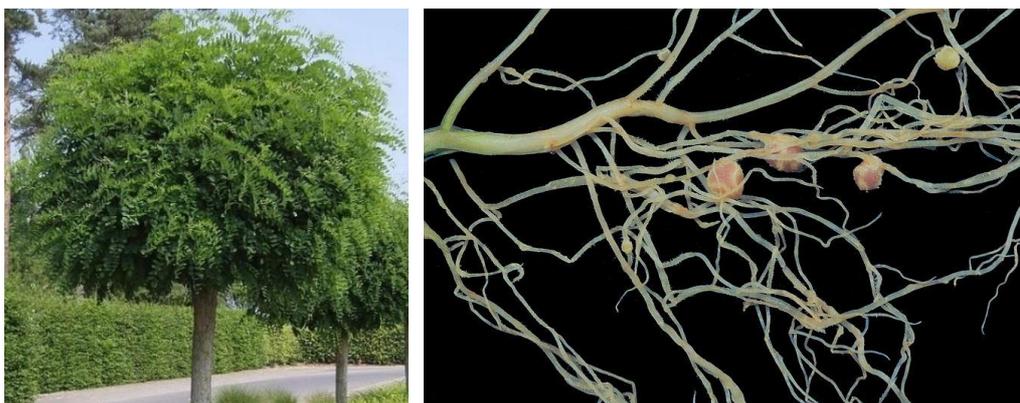


Figure 7 The Robinia tree (left) is capable to fix nitrogen in the soil using its root nodules (right).
[Picture source: Wikipedia Commons]

3.2 FERTILIZER APPLICATION

There are significant differences in effectiveness of nitrogen uptake in plants depending on the type of fertilizer (in the form of animal manure, sewage sludge or artificial fertilizer made from natural gas), fertilizer dosage, types of crops, soil characteristics and weather conditions. Consequently, there may also be substantial differences in leaching of nitrogen to the local natural environment.

One influencing parameter here is related to the origin of the nitrogen in the fertilizer. When using organic fertilizer, the reactive nitrogen added originates from biomass. When using artificial fertilizer however, molecular nitrogen is converted to reactive nitrogen and added to the ecosystem. In the ideal case, this is therefore avoided.

The given example for wheat straw illustrates that including N based fertilizer to agricultural systems may have a substantial impact on the N balance of a bioenergy supply chain. As the wheat straw is in principle a by-product with significantly less economic value than the main product (grains), one should consider what fraction of the additional nitrogen emission should reasonably be attributed to the use of straw, and what to the use of the main product.

3.3 NO_x EMISSION OF HARVESTING AND TRANSPORTATION EQUIPMENT

The harvesting, processing and transportation of biomass is often done using mobile, diesel-driven harvesters, tractors, and trucks. The amount of NO_x emitted from such internal combustion engines during the supply chain depends on the effort required in terms of mechanical and thermal energy input, transportation distance, and the efficiency of the equipment used. It is obvious that large variations may occur from case to case.

For the case of Finland, energy efficiency and emissions for machinery used in the logistical chain of forest wood supply were assessed for 2021 (Haaviko et.al, 2022) based on available statistical data for Stora Enso WSF's industrial roundwood harvest of 8.9 million solid m³. The study derives specific NO_x emissions for cutting, forwarding and transportation equipment respectively 3.5, 4.1 and 2.1 g per m³ of harvested roundwood. Using an average energy content of 7 GJ/m³ of the wood used in combustion plants (Ministry of Agriculture and Forestry, Finland, 2022), this leads to an emission factor of 1.4 g NO_x/GJ of fuel. This is relatively low in comparison to the typical NO_x emissions from biomass boilers (typically approx. 50-100 g NO_x/GJ).

3.4 NO_x FORMATION DURING END-USE

In any combustion plant, NO_x (and eventually also NH₃ slip in case the plant is equipped with de-NO_x equipment) may be formed and subsequently released to the environment. In contrast to combustion of natural gas where molecular nitrogen (N₂) is partly converted to NO_x due to the high flame temperatures, the combustion temperatures for biomass are typically too low to form thermal NO_x, therefore most if not all NO_x formed during combustion originates from fuel nitrogen. The conversion rate of fuel nitrogen to NO_x shows a decreasing dependency on nitrogen concentration, as is shown below. For a modern furnace equipped with staged combustion, typically between 10-70% of fuel nitrogen is converted to NO_x, the other 30-90% is converted to inert N₂. It is also interesting to see that for nitrogen-rich species with fuel-N contents exceeding 0.5%, only about 10% is converted to NO_x. For woody biomass with less than 0.5% fuel N, typically about 30-50% is converted to NO_x.

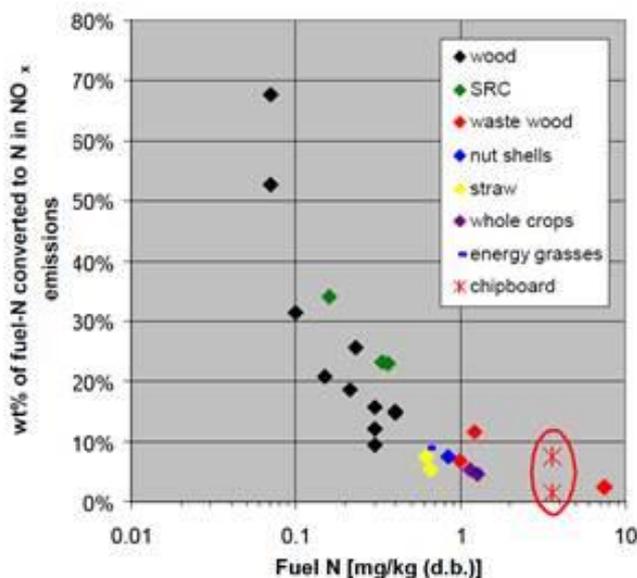


Figure 8 Conversion of fuel nitrogen to NO_x for various fuels [Hesch, T. et. al, 2011]

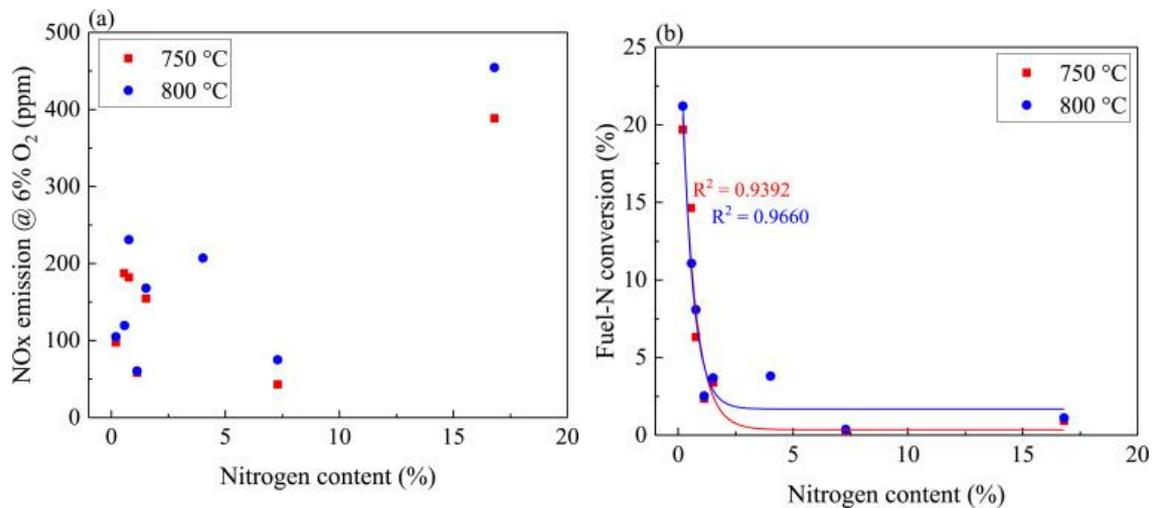


Figure 9 Correlation of N content and (a) NO_x emissions as well as (b) fuel-N conversion to NO_x [Pin Wei Li et. al., 2020]

The above emissions can be related to fossil-based alternatives. A typical natural gas fired boiler has a significantly lower NO_x emission than a typical biomass boiler. For instance, under the Dutch Activiteitenbesluit¹, natural gas fired boilers need to comply with an emission limit of 70 mg NO_x @ 3% O₂, which is equivalent to 58 mg NO_x @ 6% O₂. A biomass boiler of the same capacity needs to comply with an emission limit of 300 mg/m³ @ 6% O₂, which is significantly higher. The potential impact on increased nitrogen deposition in the area surrounding the plant is therefore also more prevalent. The fundamental difference is however that any reactive nitrogen from a gas fired boiler is an addition to the ecosystem, while combustion of biomass fuel in a biomass boiler causes a reduction of reactive nitrogen in the ecosystem.

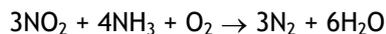
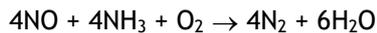
Table 1 comparison of stack emissions from biomass boiler and a natural gas boiler. Assumed is woody biomass with a LHV of 11 GJ/ton. For both boilers, an efficiency of 90% is assumed.

	Wood chips	Natural gas
specific flue gas production (m ³ flue gas@ 6% O ₂ per kg fuel)	4.19	10.65
NO _x emission limit value (mg/m ³ @ 6% O ₂)	300	58
NO _x emission factor (g/GJ heat)	114.3	19.6

¹ See <https://rwsenvironment.eu/subjects/air/mid-sized-combustion/>

3.5 POST COMBUSTION DENOX INSTALLATIONS

Depending on local emission limits imposed, a biomass combustion plant may be equipped with Selective Non-Catalytic Reduction (SNCR) systems typically consist of ammonia or urea injection in the post combustion chamber at approx. 950-980 °C, eventually followed by catalytic conversion in the presence of a platinum, titanium, or vanadium oxide catalyst at approx. 250 °C (Selective Catalytic Reduction, SCR). The stoichiometric equations for NO and NO₂ are:



A combination of SNCR and SCR systems can result in a combined post treatment reduction of up to 90%, the remainder being emitted as harmless N₂. One should however take care that the above reduction reactions are carried out under optimal conditions. SNCR systems with urea injection should be using injection lances that distribute ammonia or urea with the optimal spray pattern for a given furnace geometry and operated under the optimal temperature window. Similarly, sufficient and clean catalytic area should be available at the right temperature to provide optimal conversion in the SCR system. Ammonia that has not reacted, will be emitted as ammonia slip from the chimney, and should also be taken into consideration when evaluating the reactive nitrogen balance. Typical concentrations of ammonia slip are in the order of 5 mg/m³ @ 6%O₂. There are examples of biomass combustion plants equipped with flue gas condensation, where the acid environment of the condensate helps to further reduce ammonia slip.

3.6 LOCAL NITROGEN DEPOSITION RATES INFLUENCES PLANT TYPE AND NITROGEN CONTENT

Local nitrogen emission and deposition rates strongly vary by geographical region due to differences in emissions from industry, traffic, and cattle breeding. Figure 10 shows the differences in emissions between central western EU and north EU in emissions from these sectors.

As a result of such differences, the presence of some types of nitrogen abiding plants (e.g. nettles) is favoured in areas with high deposition, while other species (e.g. heather) may dominate in areas with low nitrogen deposition. Once the critical deposition value for nitrogen is exceeded, maintaining the original habitat may become problematic. For this reason, local authorities are already imposing strict limits on nitrogen emissions from some relevant sectors. In cases where the critical deposition value is already exceeded, permits for installations that result in additional nitrogen deposition may not be issued if an activity has a net contribution to nitrogen deposition.

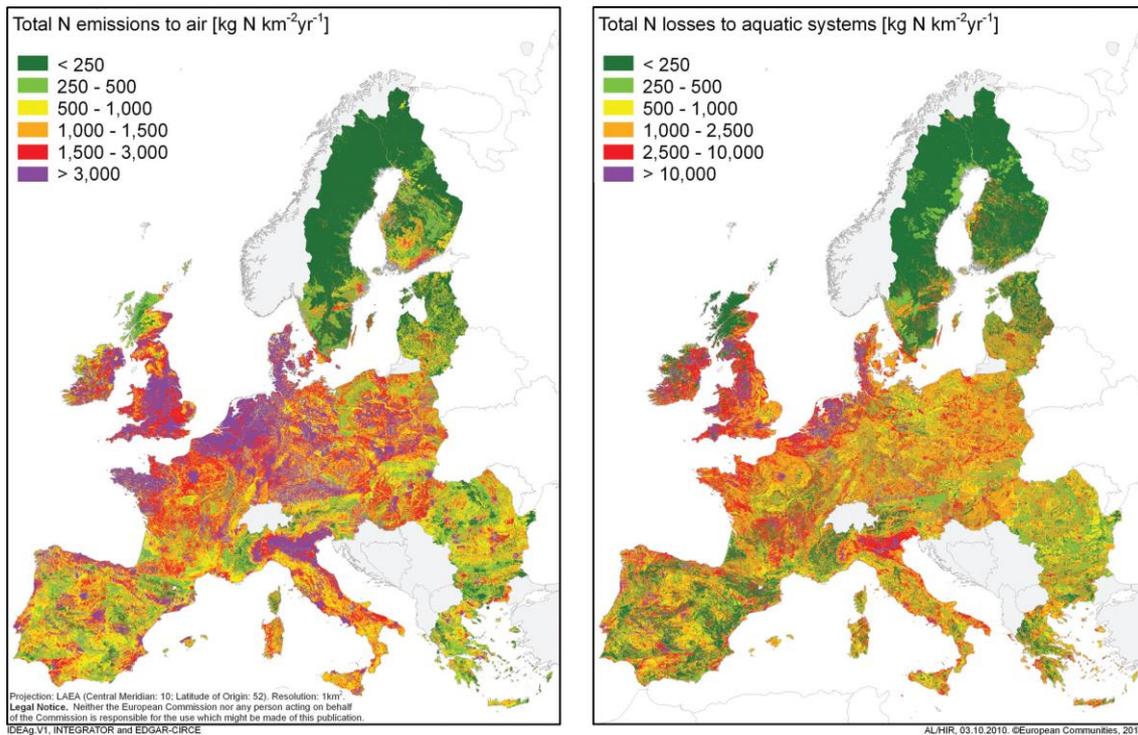


Figure 10 Distribution of reactive nitrogen emissions across Europe (kg N per km² for 2000) including emissions to air as NO_x, NH₃ and N₂O, and total losses to aquatic systems, including nitrate and other N_r leaching and wastewaters [Sutton et al, 2011]

One of the possible mitigating measures to restore the original habitat may be to remove nitrogen rich vegetation from the region for use elsewhere (e.g. as a fuel). An example of removal of heather, enriched in grass due to nitrogen deposition, is shown in Figure 11.



Figure 11 Removal of nitrogen rich top soil to restore the original heatherland vegetation [Nationaalpark Dwingelderveld, 2022]

3.7 SITING OF THE COMBUSTION SYSTEM

With the production of biomass fuel, reactive nitrogen is removed from the harvesting area. Although this removal itself might be beneficial to withstand eutrophication in this area, the concentrated release of (although less) reactive nitrogen on a single location from a combustion plant might cause unwanted effects on local air quality around the plant or nitrogen deposition in a nature conservation area nearby. It might therefore still be required to analyse/quantify the effects on nitrogen deposition using dedicated models that take into account local meteorological conditions, atmospheric chemical reactions, local vegetation, background deposition, etc. and consider if the additionally caused deposition can be deemed acceptable from an ecological perspective. The effects on deposition increase with plant size and emissions, therefore it is particularly relevant to carry out such assessments for larger combustion plants. As a result of such an analysis, one might decide to e.g. relocate a combustion system, modify its stack height or take measures to protect the natural habitat in the affected area in another manner.

4 Conclusions and outlook

During their growth cycle, plants and trees absorb nitrogen from their environment and store it in cell tissue. Except for a few plant and tree species that are capable to store molecular nitrogen directly from the atmosphere, this nitrogen in lignocellulosic cell tissue solely originates from reactive nitrogen in the form of fertilizer, NO_x or NH_3 induced acid rain or any other source.

If such biomass is burned in a modern boiler, a small fraction of the nitrogen contained in the fuel is converted to NO_x , however most of the fuel nitrogen converts to harmless N_2 . Even when taking into account indirect emissions of reactive nitrogen during harvesting and transport, less reactive nitrogen is typically emitted than what is absorbed from a systems perspective, therefore a net reduction of reactive nitrogen in the ecosystem can be achieved.

In case there is a need to reduce reactive nitrogen load on nearby nature conservation areas there are a number of influencing factors to consider, such as biomass species, application of fertilizer, and NO_x emissions during the supply chain. In the ideal situation where biomass fuel is sourced from the same area where the deposition of nitrogen from NO_x emissions occurs, on any given area unit less reactive nitrogen will be deposited from burning this biomass, than what was previously absorbed. Once biomass is however transported, the fuel-caused deposition takes place in another area than where the biomass was grown. Although this may be beneficial for the area where the biomass is harvested, it can be unfavourable for the area around the combustion plant, particularly if the critical deposition value for nitrogen is already exceeded or if ambient concentration levels of NO_x are already high. In the absence of post combustion de NO_x equipment, the NO_x emission per GJ of heat is approx. 6 times higher than that of a natural gas fired boiler. Replacement of a natural gas fired boiler by a biomass boiler may therefore not be acceptable due to its negative impact on local air quality, and particularly for larger plants more stringent ELV's resulting in applied SNCR and/or SCR may be imposed.

Based on the analysis carried out in this study, a follow-up study is performed in the current triennium (2022-2024) by IEA Bioenergy Task 32, containing the following aspects:

- A detailed literature review on factors influencing NO_x formation from biomass combustion. The review shall focus on publications dealing with NO_x emissions from the combustion of different fuels, having different N contents. Woody and non-woody fuels, including a broad range of agricultural residues should be analysed. Moreover, the review will cover combustion at different scales, ranging from domestic combustion appliances (stoves, boilers, cookers, inserts) up to large scale combustion plants (with thermal output up to 500 MW), equipped with De NO_x technologies.
- Nitrogen balance calculations will be carried on relevant case studies, selected among those already published within Task 32. NO_x emissions from biomass combustion and their impact on the N cycle will be assessed, following the methods adopted in the previous studies of Enigl et al. and Callesen et al.
- Results of the literature review and case study analysis will set the scientific basis to provide advice and recommendation for policymakers.

5 References.

Callesen et al. (2011). Efficient use of reactive nitrogen for cultivation of bioenergy: less is more. I. Callesen, M.S. Carter, H. Østergård, *GCB Bioenergy* (2011) 3, 171-179

European Environment Agency (2022). National Emission reduction Commitments Directive reporting status 2022, EEA Briefing. <https://www.eea.europa.eu/publications/national-emission-reduction-commitments-directive-2022/national-emission-reduction-commitments-directive> accessed on 6 December 2022.

Enigl M, Strasser C, Hochbichler C E, Schmidl C (2017). Nitrogen assessment in small scale biomass heating systems, Proceedings of the 25th EUBCE Conference, 12-15/06/2017, Stockholm, ISBN: 978-88-89407-17-2, <http://www.etaflorence.it/proceedings/?detail=14085>

Fernando K.M.C. Wibowo C, Sparkes DL (2021). Genotypic dependence of wheat species in nitrogen uptake determines by root morphology at maturity, *Tropical Agricultural Research and Extension* 24 (2)

Fowler D. et al. (2013). The global nitrogen cycle in the twenty-first century. *Phil Trans R Soc B* 368: 20130164. <http://rstb.royalsocietypublishing.org/content/368/1621/20130164>

Haavikko H., Kärhä K., Poikela A., Korvenranta M., Palander T. (2022). Fuel Consumption, Greenhouse Gas Emissions, and Energy Efficiency of Wood-Harvesting Operations: A Case Study of Stora Enso in Finland, *Croat. j. for. eng.* 43.

Hesch, T., Biedermann, F., Brunner, T., & Obernberger, I. (2011). Reduction of NO_x and PM₁ emissions from automated boilers by advanced air staging. In Proceedings of the 19th European Biomass Conference & Exhibition (pp. 874-879).

Koppejan, J. (2020). Holzheizwerk mit SNCR, SCR, Gewebefilter und NaOH-Zugabe für lokale, ultra-strenge Anforderungen, Holzenergie-Symposium, Zürich 11.09.2020, 99-106, <http://www.holzenergie-symposium.ch>.

Min. of Agriculture and Forestry, Finland (2022). Woodfuels in Energy generation in Finland.

Pin-Wei Li, Chien-Song Chyang (2020). A comprehensive study on NO_x emission and fuel nitrogen conversion of solid biomass in bubbling fluidized beds under staged combustion, *Journal of the Energy Institute*, Volume 93, Issue 1, 2020, Pages 324-334, ISSN 1743-9671, <https://doi.org/10.1016/j.joei.2019.02.007>.

Skreiberg, Ø., Hustad, J.E. & Karlsvik, E. (1997). Empirical NO_x Modelling and Experimental Results from Wood-stove Combustion, Published in "Developments in Thermochemical Biomass Conversion", Blackie Academic & Professional, pp 1462-1476.

Sutton M.-A., et al. (2011). *The European Nitrogen Assessment - Sources, Effects and Policy Perspectives*, Cambridge University Press.

Wopienka E, Nitrogen assessment in small-scale biomass heating systems, presentation at the workshop: Air as a Common Good. Policy, Actions and Technologies for Reducing Emissions from Residential Wood Burning, Verona, 21/02/2018



IEA Bioenergy
Technology Collaboration Programme

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

Contact us:
www.ieabioenergy.com/contact-us/