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# Nitrogen use efficiency and optimization of nitrogen fertilization in conservation agriculture

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## 1. Introduction

The world population increases and diets change to include more meat. Since livestock mostly have a cereal-based diet, this means global cereal yields have to double by 2050 to meet the demands of the increasing population and dietary changes. Over the past 50 years, N fertilizer application has increased 20-fold, and its application is projected to increase to 180 million tons by 2030. Also, the N fertilizer prices have climbed more than 2.5-fold over the past decade. The use and efficiency of N fertilizers is very different for different types of environment:

- **For high-input environments**, an efficient and non-polluting approach to mineral fertilizer use is essential to prevent excessive N fertilization. Excesses may cause NO<sub>3</sub>-N leaching which results in eutrophication (excessive plant growth or decay due to extra nutrients in the water) of water bodies and the destruction of water ecosystems. Over-application of N fertilizer also increases environmentally harmful NO<sub>x</sub>/N<sub>2</sub>O emissions. Worldwide, N use efficiency (NUE, see below) averages 33% in cereals, indicating substantial potential for improvement.
- **In low yielding, rainfed environments** where fertilizer use is marginal and cereal grain yields are low, the focus should be on yield and quality increase by moderate and efficient N fertilizer application rather than over-application. Small grain quality is mainly determined by grain N concentration. The higher the N concentration, the higher the farmers' profits will be, on the condition that farmers are remunerated for higher quality, which is not always the case.

Conservation agriculture (CA) has been proposed as a combination of management principles to improve water

use efficiency, reduce soil erosion and conserve resources such as farmers' time, labor and fossil fuels. It is based on three key components:

- (1) minimal soil movement, so less or no tillage operations
- (2) partial retention of residues of the crops as a soil cover
- (3) economically viable crop rotations.

Conservation agriculture has been found to change physical, chemical and biological soil quality components compared to conventional practices involving tillage and thus affects N cycling in the soil (see also the material *Conservation agriculture, improving soil quality for sustainable production systems?*). Therefore, it is likely that N fertilization will have a different effect on the crops growing under CA-conditions and hence, the fertilization will have to be adjusted in CA-based cropping systems.

## 2. The N cycle

The quantity and forms of N in the soil are constantly changing due to chemical, physical and biological soil processes. Forms of available organic N include amino acids, proteins and amino sugars. Forms of inorganic N are plant absorbable N forms ammonium (NH<sub>4</sub><sup>+</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>) and the plant toxic N forms ammonia (NH<sub>3</sub>) and nitrite (NO<sub>2</sub><sup>-</sup>). Nitrogen in the soil solution is predominately present as NO<sub>3</sub>-N which is barely adsorbed to the soil and therefore more affected by leaching, as well as NH<sub>4</sub>-N which, however, is largely bound to soil particles.

Nitrogen can enter the soil from the atmosphere through dry and wet N deposition, organic and synthetic fertilizers and N fixation. Through decomposition of crop residues, N will be added to the organic N pool. The N content in the soil can be reduced by processes like ammonia (NH<sub>3</sub>) **volatilization**, where gaseous NH<sub>3</sub>-N is lost to the

atmosphere, and emission of denitrification products ( $N_2$ ,  $N_2O$ ,  $NO$ ). In case of excessive wetting, mineral nitrogen (particularly  $NO_3^-$ ) may leach beyond the reach of root crops (**leaching**, downwards movement of  $NO_3^-$  through the soil by water percolation and water flow, Figure 1). Mineral N in the soil can also be used up through the N uptake of the crop.

The soil N cycle is heavily affected by **mineralization**, the transformation of organic N in soil organic matter (SOM) and manure into inorganic N, ultimately forming ammonium, by the activity of fungi and bacteria (Figure 1). Mineralization processes are enhanced by warm and wet climatic conditions and intensified in well aerated soils. **Immobilization** describes the removal of inorganic N from the soil solution by microorganisms. These microorganisms break down crop residues with a high C/N ratio and satisfy their energy demands by utilizing the residue carbon components. However, microorganisms also use the available crop residue and fertilizer N to form proteins for their own growth. A C/N ratio of >30 in crop residues provides readily decomposable C compounds which leads to extensive N immobilization.

**Nitrification** is the microbial soil process where  $NH_4-N$  is converted into  $NO_3-N$  by the microbes *Nitrosomonas* and *Nitrobacter*. **Denitrification** is the opposing biological process to biological fixation in which ionic

N oxides ( $NO_3^-$  and  $NO_2^-$ ) are reduced stepwise by reductase enzymes to gaseous oxides (nitric oxide,  $NO$ ; and nitrous oxide,  $N_2O$ ).

Nitrogen dynamics in agricultural systems are highly influenced by the large quantities added as N fertilizers. N supply to soils increases productivity and biomass accumulation in the short-term, however, increases in SOM might accelerate N dynamics and thus emission of  $N_2O$ , a greenhouse gas.

The different steps of N uptake, assimilation and recycling to the final deposition in the grain can be divided into two general stages for N use in the crop's life cycle:

- **Vegetative phase:** N is absorbed overwhelmingly in its inorganic form by plant roots. After entering the plant, the vegetative phase starts. In this vegetative stage, young leaves and roots serve as sinks for inorganic N uptake and synthesis.
- **Reproductive phase:** The accumulated N in shoots, leaves and roots is remobilized by protein hydrolysis. Amino acids are then exported to the grain. Nitrogen availability during grain filling can be increased by addition of N in combination with an adequate soil moisture level, which in arid zones may require additional irrigation. The majority of N remobilization takes place during senescence. However, this kind of N

recycling can also occur before flowering for the synthesis of new proteins in developing organs, which highlights the simplicity of separating the plant N cycle into only two phases.

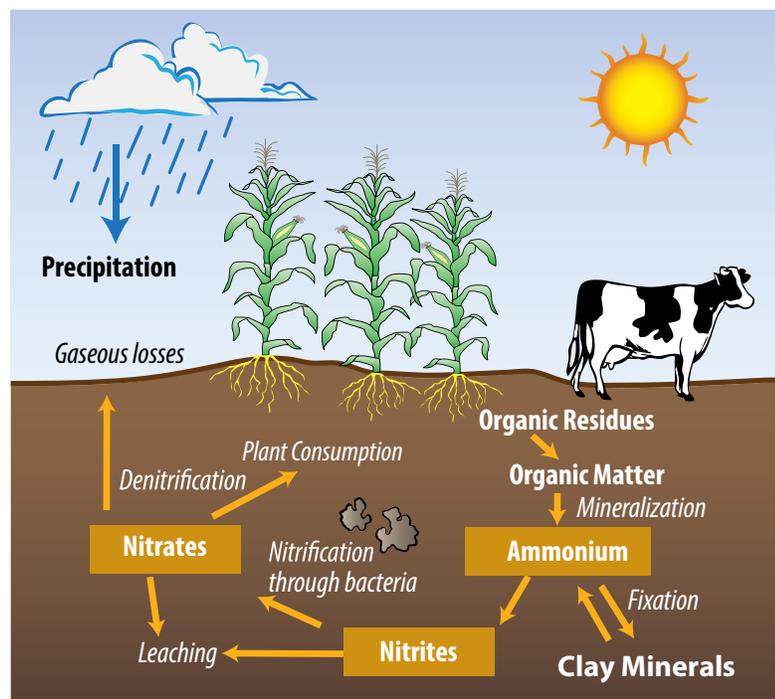


Figure 1: The nitrogen cycle. The main pool of N in the soil is in the form of nitrate ( $NO_3^-$ ), nitrite ( $NO_2^-$ ) and ammonium ( $NH_4^+$ ). (adapted from [www.windows2universe.org](http://www.windows2universe.org))

### 3. The effects of changes in soil properties and processes in CA systems on the N cycle

The tillage system determines the placement of crop residues. Crop residues are incorporated into the soil with conventional tillage, whereas crop residues remain at the soil surface in a CA system which influences the chemical, physical and biological soil processes. Usually, the incorporation of plant residues by tillage into the soil accelerates C and N mineralization by making SOM within the macroaggregates more available to microorganisms. If residues stay on top of the soil, they are less susceptible to microbial breakdown.

The effect of CA on the processes that cause N loss after fertilization is now discussed.

- **N immobilization:** Crop residues with low N concentrations ( $C/N > 30$ ) cause temporary net N immobilization after which microbial growth is limited. Conservation agriculture systems have been found to temporarily increase N immobilization due to slower residue decomposition. Short term N immobilization can be compensated for by increased application of N fertilizer, especially in the first years of conversion to conservation agriculture.
- The average global N losses by **volatilization** are estimated to be 7% for industrialized and 18% for developing countries. Conservation agriculture systems are reported to have higher N losses due to increased volatilization of  $NH_3-N$  and insufficient fertilizer incorporation.
- Crop residue retention and tillage affect processes, which lead to positive and negative effects on **denitrification**. On the one hand, the residue retention of CA often increases the soil water and SOM content compared to conventional tillage. This favors  $N_2O$  emissions. On the other hand, residue retention also results in decreased soil temperature and a better soil structure – and thus it improves aeration, which means less anaerobic sites in the soil. This may reduce  $N_2O$  emissions.
- Soils with zero tillage or permanent raised beds combined with residue retention have improved aggregate stability, which results in higher infiltration rates. This might increase **N leaching losses**. Leaching losses in CA systems could also increase due to an

increased number of earthworm biopores. On the other hand, slower nitrification in zero tillage during fallow periods could reduce the potential for  $NO_3$  leaching.

The key element in these processes seems to be the soil organic biomass. In the long term, CA increases SOM and hence soil microbial biomass. Soil microbial biomass plays an important role in nutrient mineralization, mobilization and immobilization and functions as source and sink of soil nutrient availability. However, the problem of the lower N mineralization in CA systems should be resolved. Two actions could be considered with regard to the residues kept in the field, but they need to be evaluated within the context of the production system:

- The use of more finely or macerated residues, which will decompose more rapidly because microbial populations can colonize and decompose straw more quickly if the substrate surface is increased.
- Adjust the amount of residues retained.

### 4. N use efficiency (NUE)

#### 4.1. Definition

Different definitions and perspectives exist for NUE and its components. One of the definitions states that NUE is the ratio of grain yield per unit of available N in the soil, including the present residual soil N and fertilizer N. The easiest way to calculate NUE is based on a partial N balance:

$$NUE = (N \text{ exported from field into crops}) / (N \text{ applied})$$

However, not all available plant N comes from N fertilizer. NUE is a function of soil structure, climatic conditions, interactions between soil and bacterial processes and the nature of organic and inorganic N sources, which is not included in the formula above. For a summary on more ways to define NUE, we refer to Grahmann et al. (2013).

#### 4.2. Methods to determine NUE

Whole-plant physiological studies combined with  $^{15}N$  labeling experiments, preferentially performed under field conditions, can be used to identify NUE key components and genetic variability of the dynamics of N distribution within the plant with high accuracy.

As mentioned before, several processes like N losses are not included in the formula for NUE. The most important losses in CA systems are nitrate leaching and volatilization.

- **Nitrate leaching** can be measured by ion exchange resin cartridges, which determine cumulative leaching losses at the plot-scale. The resin cartridges are installed below the rooting zone by digging a trench next to the plot and tunneling an approximately 50 cm deep horizontal access to an undisturbed part of the plot. The resins stay in place for the entire crop cycle and give an accumulated value of nitrate lost through the soil profile. After harvest, resin cartridges are removed from the soil and their content in attached ions is analyzed.
- **Volatilization losses** of gaseous N compounds can be measured with closed chamber systems. The collected gases can be analyzed directly in the field by portable devices or extracted in a syringe and afterwards injected into evacuated vials, which are then closed with a rubber stopper. Subsequently, these vials are analyzed for their gas concentrations by chromatography.

Simulation models represent a promising tool in identifying best management practices with improved NUE, advanced nutrient management and reduced N losses, while reducing the necessary number of field experiments. Simulation models are based on, and developed with, field experiment data. Once calibrated, the model can be used for other climatic, agronomic or environmental conditions. An appropriate model should include soil, water and climate data to evaluate mineralization, immobilization, turnover processes and N cycling and to reveal alternatives to reduce N losses by leaching, gaseous emissions or surface runoff. Each model has to be configured and calibrated for the unique site conditions and cropping system. For N management modeling techniques, previous information about soil type, crop variety, soil residual  $\text{NO}_3\text{-N}$  and other soil parameters such as water content, SOM, pH or CEC and management practices are a key precondition for a successful simulation. Two examples of models used for reduced tillage systems are PASTIS (Prediction of Agricultural Solute Transformations In Soils) and NDICEA (Nitrogen Dynamics In Crop rotations in Ecological Agriculture).

## 5. Nitrogen use efficiency in conservation agriculture

### 5.1. State of the art

Only a few recent studies on NUE and N fertilizer management in CA systems are available. In CA, effects of N fertilizer can be noticed in the following cropping seasons over several years. This is especially the case when fertilizer is applied in combination with residue retention since this can increase temporary immobilization of fertilizer, which is released in the following years. Research results on the effect of rotation in CA systems on NUE are inconsistent, but most studies found negative effects of crop monoculture on yield and NUE and positive effects of legumes included in the rotation.

### 5.2. Adjusting N fertilizer management in CA to improve NUE management

Nitrogen fertilizer management can be divided into four different components: amount, type, timing, and placement of N fertilizer.

#### 5.2.1. N application rate

The quantity of applied N fertilizer is the most yield determining factor, followed by N source, timing and application method. The optimum amount of fertilizer N can be calculated by pre-planting soil samples or sensor-based N management and varies within the intensity and yield potential of the CA production system. A valid N rate assessment takes into account:

- the productivity potential of the soil
- previous crops
- ratio of the price of N fertilizers to the crop value
- minimizing environmental losses.

In all cases, an over-application of N should be avoided. Symptoms of excess are reduced yields because the crop is more susceptible to pests and diseases and also to lodging. Usually, the plants start to reduce remobilization of N to the grain and continue their vegetative growth.

Sensor-based N management relies on precision CA which refers to the combination of minimum soil movement, residue retention, crop rotation and planting of improved

varieties with spatial technologies such as GPS, remote sensing and GIS to adjust fertilizer application to plant demand based on monitoring crop growth to augment NUE and yield. An NDVI sensor can be utilized to follow crop development throughout the season such as the GreenSeeker®-handheld sensor (NTech Industries, Inc., Ukiah, California, USA). In combination with a well-fertilized reference crop the NDVI sensor can be useful to provide precise information about crop N demand which helps reduce fertilizer costs and N losses.

### 5.2.2. Type of fertilizer

Nitrogen fertilizers vary in their concentrations of N and in the form in which they are added to soils and crops. The choice of fertilizer depends on the soil pH, soil moisture content, available soil N, fertilizer disposability, availability of fertilizer application equipment and costs per unit of N ha<sup>-1</sup>. There is no universal recommendation available for the best type and amount of fertilizer. Farmers need to evaluate which N source will be adequate for their specific conditions in order to keep volatilization losses to a minimum and to overcome the effects of N immobilization.

Urea is a very common fertilizer, but it can cause greater N losses under CA due to increased urease activity in crop residues. Application of foliar applied urea N at or after anthesis was reported to be highly efficient at increasing grain protein and hence bread-baking quality in conventional systems. Unfortunately, literature on the effect of foliar N application in CA is scarce.

Animal manure can be an alternative on-farm resource to compensate for increasing costs of mineral N and therefore help to reap value from farm wastes. More research is needed to optimize application methods and timing to reduce volatilization losses when using animal manure in CA systems.

### 5.2.3. Timing of N application

N losses can be reduced by a better synchronization of N application and crop uptake needs. If mineral N fertilizer is applied during the peak plant N demand, immobilization and losses from the soil-plant system can be reduced and hence NUE can be increased.

For a long time now, it has been assumed that early season N applications optimize grain yield and late season applications provide and optimize grain protein

concentration. Most of the available research has been conducted under tilled conditions. However, the timing and rate of N fertilization significantly affects yield, NUE and its components such as N losses.

Also, irrigation can contribute to an efficient uptake of late season N fertilizer. Under irrigated conditions, late season N application is more likely to contribute to a more efficient N uptake compared to rainfed production systems. Crop residues that help to increase soil moisture could also contribute to improving N fertilizer distribution in the soil and N uptake by the plants unless residues immobilize N. In summary, N fertilizer use efficiency should be increased by applying N during the periods of highest N plant demand and by delaying the early or pre-plant N application. However, for CA cropping systems, research regarding the optimization of timing for N fertilization is largely lacking.

### 5.2.4. Fertilizer application method

Small grain cereals take up 90% of their N before their flag leaf stage of development. Surface-applied residues with a C/N ratio > 30 bind the fertilizer N during the decomposition process by microorganisms when fertilizer is broadcast, whereas subsurface fertilizer placement avoids the direct contact of fertilizer N with crop residues and could be useful to reduce the potential for volatilization, denitrification and immobilization. Subsurface N banding in CA appears to be an efficient application method to improve fertilizer recovery compared to N application by broadcast application. The reduced NUE in CA found in some studies could be due to broadcast application of N fertilizer. There is a lack of suitable and inexpensive fertilizer equipment for subsurface application in CA. These implements could be utilized by small- and medium-sized farmers for appropriate and efficient application of their N fertilizer. Scientists and local machinery manufacturers should combine their efforts to develop the necessary machinery and to promote new N fertilizer application methods. Subsurface application by shallow disk injection, chisel injection, aeration infiltration or pressure injection of cattle and swine manure can reduce NH<sub>3</sub> volatilization and decrease nutrient losses in runoff but could potentially increase N<sub>2</sub>O emissions.

## 6. Nutritional quality of agricultural products

Most studies focus on yield and crop nutritional quality is often neglected in the research. Cereal grain quality, correlated with grain protein concentration, is particularly important for small-scale farmers who grow cereals as cash crops and are remunerated for quality. There are different factors that can affect the grain protein concentration:

- It can be increased by **N fertilizer application** above the level of fertilizer that overcomes N as the most limiting factor for crop yields.
- **Tillage method** may affect the protein content and quality of wheat, because it affects soil moisture content, nutrient availability, evaporation and soil temperature.
- **Increasing rotation complexity**, by including legumes, is expected to produce greater yields and grain protein concentrations across soil fertility regimes, particularly in low-input environments.

There are only few and inconsistent studies available on the effect of CA on wheat quality. Contrasting comparisons between CA and conventional tillage practices on grain protein concentrations and other quality traits have been reported in literature. Explaining the changes in wheat grain quality between both systems will require thorough analysis of the N cycle, which is especially influenced by residue management.

## 7. Chemical compounds delaying and stabilizing N release from fertilizers

Synthetic fertilizer additives such as urease or nitrification inhibitors and slow-release fertilizer were proposed to improve NUE. Urease inhibitors can potentially reduce volatilization losses by preventing the breakdown of urea and increasing the probability that the fertilizer will be absorbed into the soil right after a rain event. Again most studies were conducted under conventional conditions and reports are lacking for CA.

## 8. Conclusions and future challenges

The available data demonstrate that interactions between components of CA and their effects on crop yield and crop quality parameters are complex and often site-specific. Based on the little available data, CA seems to have lower NUE rates than conventional systems, which is largely due to N fertilizer immobilization through crop residues and increasing fertilizer rates with CA. More research is needed to confirm these results in different cropping systems and environments. Long-term, field-based studies could provide a better understanding of the effect of CA based technologies on N cycling. There is also a clear need for applied research on how to adjust N fertilizer management and machinery and to translate results into farmer recommendations. Recommendations will be site- and farm-specific and will depend on abiotic factors such as climate, type of soil, amount of rainfall, and temperature, and also agronomic practices like rotation, intensity of tillage (zero-reduced-minimum), the quantity of crop residues left on the field and finally the objectives of the farmer to produce higher crop yields or enhanced cereal quality.

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