ABSTRACT

Velthof, G.L. & O. Oenema, 2001, *Effects of ageing and cultivation of grassland on soil nitrogen*. Wageningen, Alterra, Green World Research. Alterra-rapport 399. 56 pp. 12 figs.; 16 tables; 50 refs.

Nitrogen losses from agriculture in the Netherlands have to be strongly decreased because of national and international policy (e.g. Nitrate Directive). The cultivation of grassland when grassland is renewed or converted into arable land may enhance net nitrogen mineralization and, thereby, nitrogen losses via leaching and denitrification. These nitrogen losses can be decreased by adjustment of management, but a good insight in the soil processes during ageing and after cultivation of grassland is required. A literature study was carried out to quantify the effects of ageing and cultivation of grassland on nitrogen losses from the soil. The study shows that the risk on losses increases when grassland age increases, the period between cultivation and reseeding increases and the N uptake capacity of the next crop decreases. In the Netherlands, only a few studies have been carried out and, especially, a quantification of the effects of cultivation on N losses under Dutch conditions is lacking. It is recommended to set up integral field studies in which both the agricultural and environmental effects of grassland cultivation are quantified. The results must be used to develop measures and tools to achieve environmental and agricultural sound systems of permanent and temporal grasslands.

Keywords: cultivation, denitrification, grassland, leaching, mineralization, nitrogen, ploughing, reseeding

ISSN 1566-7197

This report can be ordered by paying 40,00 Dutch guilders (€ 18) into bank account number 36 70 54 612 in the name of Alterra, Wageningen, the Netherlands, with reference to rapport 399. This amount is inclusive of VAT and postage.

P.O. Box 47, NL-6700 AA Wageningen (The Netherlands).
Phone: +31 317 474700; fax: +31 317 419000; e-mail: postkamer@alterra.wag-ur.nl

Project 317-11106 [Alterra-rapport 399/HM/11-2001]

Contents

Samenvatting

Korte samenvatting

In het kader van de Nitraatrichtlijn van de EU en het Nederlandse mestbeleid moeten de stikstofverliezen uit de landbouw sterk worden verminderd. Grondbewerking bij graslandvernieuwing en wisselbouw van bouwland en grasland leidt tot een sterke toename van de stikstofmineralisatie in de bodem die kan leiden tot forse stikstofverliezen via nitraatuitspoeling en denitrificatie. Door maatregelen kunnen deze stikstofverliezen worden beperkt, maar hiervoor is een goed inzicht nodig in de bodemprocessen. Er is een literatuurstudie uitgevoerd met als doel het kwantificeren van de effecten van scheuren van grasland en de leeftijd van grasland op stikstofverliezen uit de bodem. De studie laat zien dat het risico op stikstofverliezen toeneemt naarmate grasland ouder wordt, de periode tussen tijdstip van scheuren en het tijdstip van (her)inzaai toeneemt en de stikstofopname door het volggewas kleiner is. Deze conclusies zijn vooral gebaseerd op buitenlands onderzoek, aangezien in Nederland weinig experimenteel onderzoek is uitgevoerd naar stikstofverliezen bij het scheuren van grasland. Er wordt aanbevolen om in Nederland integrale studies uit te voeren waarin zowel de landbouwkundige en milieukundige gevolgen van graslandvernieuwing en wisselbouw worden gekwantificeerd. Dit onderzoek moet leiden tot indicatoren en maatregelen waarmee landbouwkundig en milieukundig verantwoorde systemen van blijvend grasland en wisselbouw kunnen worden gerealiseerd.

Inleiding

Het grootste deel van het grasland (>90%) in Nederland is blijvend grasland. De graszode van het meeste blijvende grasland wordt één keer in de 5 tot 10 jaar vernieuwd. Dit kan op verschillende wijzen; van volledig omploegen (scheuren) en vervolgens inzaaien tot doorzaaien met een beperkte grondbewerking. Bij tijdelijk grasland, in systemen met wisselbouw, wordt grasland na een aantal jaren omgezet in bouwland en wordt het bouwland na een aantal jaren weer omgezet in grasland. Ongeveer 100000 ha grasland wordt jaarlijks in Nederland vernieuwd of omgezet tot bouwland. Het ploegen (of andere grondbewerking) van grasland bij vernieuwing of wisselbouw leidt tot een sterke toename van de netto stikstofmineralisatie die kan leiden tot verliezen van stikstof (N) via nitraat (NO_3) uitspoeling en denitrificatie. In het kader van de Nitraatrichtlijn van de EU en het mestbeleid (oa. stelsel van regulerende mineralenheffing MINAS) in Nederland moeten de N-verliezen uit de landbouw sterk worden verminderd. Om de N-verliezen bij graslandvernieuwing en wisselbouw te beperken, is een goed inzicht nodig in de processen die in de bodem optreden tijdens het ouder worden van grasland en na grondbewerking.

Doel van de studie

In dit rapport worden de resultaten van een literatuurstudie weergegeven naar de effecten van scheuren van grasland en het ouder worden van grasland op de processen in en N-verliezen uit de bodem. De literatuurstudie was gericht op experimenteel onderzoek in Nederland en het buitenland. De doelstellingen van de literatuurstudie waren:

i) het kwantificeren van het beloop van de N-accumulatie in grasland in de tijd;
ii) het kwantificeren van de effecten van leeftijd en scheuren op N-mineralisatie; nitraatuitspoeling, denitrificatie en de stikstoflevering in grasland en
iii) het aangeven van de belangrijkste kennishiaten.

Stikstofaccumulatie in de bodem van grasland

De hoeveelheid N in levende wortels en stoppels neemt met ongeveer 20 tot 30 kg N per ha per jaar toe gedurende de eerste vijf jaar na inzaai; daarna vlakt de toename af. De totale hoeveelheid organische N in de bodem neemt jaarlijks met 20 tot 350 kg N per ha toe gedurende de eerste 10-30 jaren na inzaai. Deze N-accumulatie neemt in verloop van de tijd af en na 30-100 jaar is een evenwichtssituatie bereikt waarin de totale hoeveelheid organische N in de bodem min of meer stabiel blijft, afhankelijk van de omstandigheden. De snelheid van de N-accumulatie hangt sterk af van het initiële organische N-gehalte, N-bemesting met dierlijke mest en kunstmest, beweiding en grondsoort, maar er zijn niet voldoende gegevens in de literatuur om de effecten van deze factoren goed te kwantificeren. De grootte van afname in de hoeveelheid bodem-N na vernieuwing en het omzetten van grasland naar bouwland is slecht gekwantificeerd.

Netto stikstofmineralisatie[1]

De schatting van de netto N-mineralisatiesnelheden in graslanden varieert van 100 tot meer dan 250 kg N ha^{-1} $jaar^{-1}$. Deze variatie wordt veroorzaakt door verschillen in ouderdom van het grasland, grondsoort, graslandmangement, drainage, proefomstandigheden en –uitvoering en meetmethoden. De N-mineralisatie neemt toe bij ouder worden van grasland (met een factor 1,3 tot 2,9 in de eerste 10 jaren). In veel studies worden de N-mineralisatie gekwantificeerd in incubaties met bodemmonsters; de gegevens van deze studies zijn vaak niet goed te vertalen naar een jaarlijkse N-mineralisatie onder veldomstandigheden. Engelse studies laten zien dat de netto stikstofmineralisatie na scheuren van grasland meer dan 500 kg N ha^{-1} $jaar^{-1}$ kan bedragen indien oud grasland (ouder dan 40 jaar) wordt omgezet in bouwland. In Nederland komen graslanden die meer dan 30 jaar niet zijn gescheurd zelden voor en er zijn niet voldoende experimentele gegevens om de effecten van scheuren van jonge graslanden op N-mineralisatie te kwantificeren. Modelberekeningen geven een netto N-mineralisatie van minder dan 250 kg N ha^{-1} $jaar^{-1}$ aan na het scheuren van grasland dat jonger dan 5 jaar is.

---

[1] netto N-mineralisatie is het verschil tussen N-mineralisatie en N-immobilisatie: de netto hoeveelheid minerale N die vrijkomt bij de afbraak van organische N

Stikstofleverend vermogen[2]

In het huidige bemestingsadvies voor grasland in Nederland wordt rekening gehouden het het N-leverend vermogen van de bodem. In het bemestingsadvies is het N-leverend vermogen van minerale gronden afhankelijk van de textuur en het N-gehalte in de bodem en dus van de leeftijd van het grasland. Het N-leverend vermogen van minerale gronden varieert van 50 to 300 kg N per ha per jaar en die van veengronden van 230 to 300 kg N per ha per jaar. Het N-leverend vermogen van veengronden hangt af van de grondwaterstand. Scheuren en herinzaai in het voorjaar leidt tot een hoger N-leverend vermogen dan scheuren en herinzaai in het najaar.

Stikstofverliezen

Er zijn indicaties dat de N-verliezen via uitspoeling en denitrificatie (inclusief lachgasemissie) toenemen bij het ouder worden van grasland, maar er zijn onvoldoende experimentele gegevens om kwantitatieve relaties af te leiden tussen ouderdom van grasland en de N-verliezen. De tijd tussen ploegen en opnieuw inzaaien van grasland is zeer belangrijk, aangezien in deze periode een grote N-mineralisatie en beperkte N-immobilisatie in de bodem en N-opname door het gras optreedt. De literatuur geeft duidelijk aan dat de N-verliezen toenemen naarmate de tijd tussen ploegen en herinzaai toeneemt, met name in de herfst. Scheuren van grasland van 2, 5 en 50 jaar en het direct inzaaien in voorjaar leidde in een studie in Engeland tot een vergelijkbare nitraatuitspoeling als niet gescheurde grasland. Dit werd toegeschreven aan de snelle vastlegging van het gemineraliseerde stikstof door het ingezaaide gras. Bij het omzetten van grasland naar bouwland kunnen grote N-verliezen optreden (uitspoeling groter dan 100 kg N ha^{-1} yr^{-1}), omdat dan de N-mineralisatie vele malen groter is dan de N-immobilisatie in de bodem en N-opname door het gewas. Ploegen van grasland leidt ook tot een sterke toename in oplosbaar organisch N. Deze oplosbare organische N kan uitspoelen en na nitrificatie leiden tot een toename van het nitraatgehalte in grond- en oppervlakte water.

Samenvattend kan worden geconcludeerd dat het risico op N-verliezen uit gescheurd grasland (zowel blijvend als tijdelijk) groot is indien

- de periode tussen het tijdstip van scheuren en het tijdstip van (her)inzaai of het poten van nieuwe gewas groot is;
- de hoeveelheid N die door het volggewas (inclusief een eventueel wintergewas) kan worden opgenomen klein is;
- de leeftijd van het gescheurde grasland hoog is.

Het kleinste risico op N-verlies bestaat wanneer jong grasland (jonger dan 5 jaar) in het voorjaar wordt gescheurd en direct opnieuw wordt ingezaaid. Het grootste risico ontstaat indien oud grasland wordt gescheurd en de bodem gedurende langere periode (bijvoorbeeld de winter) braak blijft liggen.

---

[2] het N-leverend vermogen van de bodem is gedefinieerd als de N-opname door een onbemest gewas in de bovengrondse gewasdelen. Het N-leverend vermogen is een resultante van de netto N-mineralisatie, de atmosferische N-depositie, N-verliezen en N-opname door het gewas.

Kennishiaten en suggesties voor onderzoek

In Nederland zijn weinig studies uitgevoerd naar de kwantitatieve effecten van scheuren van grasland op N-verliezen via uitspoeling en denitrificatie. Het Nederlandse beleid is er op gericht om de N-verliezen vanuit landbouwgronden naar het milieu sterk te verminderen en het is daarom van belang om N-verliezen te verminderen die bij het ouder worden van grasland en het scheuren van grasland optreden. Belangrijke aandachtspunten voor onderzoek naar de effecten van scheuren van grasland in kader van graslandvernieuwing en wisselbouw op N-processen in de bodem zijn:

- Kwantificering van het effect van bodemtype op de netto N-mineralisatie en N-verliezen na scheuren.
- Kwantificering in meerjarige veldmetingen van de veranderingen in de hoeveelheid organische N in de bodem in verschillende graslandsystemen (blijvend nooit gescheurd, blijvend en regelmatig gescheurd, tijdelijk grasland in wisselbouw). Zowel de snelle veranderingen als langzame veranderingen in het organische stof gehalte kunnen een groot effect hebben op de N-efficiëntie van het systeem en de N-verliezen naar het milieu.
- Het testen van de hypothese dat scheuren en direct inzaaien van blijvend grasland op zand- en kleigrond in het voorjaar en begin van de zomer niet leidt tot een duidelijke toename van de N-verliezen via nitraatuitspoeling en denitrificatie in vergelijking tot grasland dat niet wordt gescheurd.
- Het testen van de hypothese dat de verhouding tussen nitraatuitspoeling en denitrificatie op zandgronden afneemt tijdens het ouder worden van grasland, omdat de hoeveelheid gemakkelijk afbreekbare organische koolstof (C) toeneemt.
- Kwantificering van de uitspoeling van opgelost organische N naar grond- en oppervlakte water na het scheuren van grasland, aangezien dit een mogelijk belangrijke emissieroute van N is die nog zelden is gekwantificeerd.
- Kwantificering van de effecten van nutrientenmanagement en teetlmaatregelen op N-accumulatie en N-verliezen, zodat maatregelen kunnen worden afgeleid die de N-verliezen na het scheuren beperken, zoals aanpassing van bemesting, beweiding, gebruik van wintergewassen en waterbeheer.
- Risico-analyse, waarbij met behulp van weergegevens, bodemgegevens en gewasgegevens een schatting wordt gemaakt van de perioden met het grootste risico op N-verliezen na scheuren van grasland.
- Ontwikkeling en testen van bodemindicatoren om het effect van type grasland (blijvend oud, blijvend jong, tijdelijk in wisselbouw) en stadium van verandering van het N-gehalte (afnemend of toenemend) vast te stellen. Deze indicatoren kunnen worden gebruikt indien beperkingen aan het scheuren van grasland worden opgelegd.

Om de effecten van ouderdom en scheuren van grasland op de N-accumulatie in en de N-verliezen uit grasland nauwkeurig te kwantificeren zijn integrale studies nodig waarin de belangrijke N-processen gelijktijdig worden gemeten in veldexperimenten. In deze veldexperimenten, met een statistische verantwoorde opzet, moeten de effecten van behandelingen (tijd en methode van vernieuwing, hoogte van N-bemesting) op de N-processen en gewasopbrengsten worden vergeleken. Deze veldexperimenten moeten op verschillende locaties (grondsoort, leeftijd grasland) worden uitgevoerd. Het wordt aanbevolen om in deze veldexperimenten ook de effecten op fosfaat en koolstof mee te nemen, aangezien scheuren van grasland kan leiden tot een toename in P-uitspoeling naar grond- oppervlaktewater en tot een toeneame van de emissie van het broeikasgas CO_2.

Een groot deel van de bovengenoemde aandachtspunten voor onderzoek naar scheuren van grasland zullen in het kader van het door het ministerie van LNV gefinancierde DLO-onderzoeksprogramma 398-II (*Emissies van stikstof en fosfaat vanuit landbouwgronden naar het milieu*) nader worden onderzocht. In de periode 2002-2005 wordt door middel van veldonderzoek onderzocht hoe groot de N- en P-verliezen uit grasland zijn bij verschillende systemen van graslandvernieuwing en wisselbouw. Op basis van de resultaten van het veldonderzoek en systeemanalyses worden indicatoren en maatregelen voor de praktijk afgeleid, waarmee zowel uit milieukundig als landbouwkundig oogpunt verantwoorde systemen van blijvend en tijdelijk grasland kunnen worden gerealiseerd.

Executive summary

Introduction

Almost all grassland (>90%) in the Netherlands is permanent (perennial) grassland. However, once in about 5 to 10 years, the grass sward is cultivated and reseeded with higher yielding grass species, after soil cultivation. Sometimes grassland is ploughed and converted into arable land and after some years the arable land can be converted again into grassland. Annually, about 100000 ha land is reseeded or converted to arable land.

In grasslands, N accumulates in soil, roots and stubble. The N accumulation in soil vanishes in time because the rate of net N mineralization increase with time. Cultivation of grassland enhances net N mineralization and increases the risk on losses via nitrate (NO_3) leaching and denitrification (including nitrous oxide emission). More knowledge of the N processes in grassland soils and the effects of ageing and cultivation on these processes is necessary to optimize the N use efficiency and decrease N losses in systems with grassland cultivation.

Aims of the study

This report presents results of a literature study on the effects ageing and cultivation of grassland on the N processes in soil. The focus of the study was on experimental research carried out in the Netherlands and elsewhere. The aims of the study were

i) to quantify the increase in the amount of soil organic N in grasslands with time,
ii) to quantify the effects of ageing and cultivation on N mineralization, N leaching, denitrification, and the N supply in grasslands and
iii) to integrate the results and to indicate the gaps in knowledge.

Nitrogen accumulation in grassland soil

The amount of N in roots and stubble in young grassland increases by 20 to 30 kg N per ha per year during the first five years. The total amount of soil organic N increase by 20 to 350 kg per ha per year, during the first 10 to 30 years after establishment of grassland on arable land. The increase in organic N in grassland vanishes after 30 to 100 years. The rate of N accumulation depends on the age of the grassland, initial organic matter content, climate, N fertilizer and manure application, grazing, and soil type. The effects of these factors can not be quantified accurately due to lack of sufficient data in literature.

Net nitrogen mineralization in grassland soil

Estimated rates of N mineralization in grassland soils vary widely because of differences in environmental conditions (age, soil type, drainage) and also because of differences in methods and procedures for estimating mineralization. The rate of N mineralization in grasslands soil tend to increase with the age of the grassland (factor 1.3 to 2.9 in 10 years). Net N mineralization after ploughing of old grasslands in the UK (>40 years) amounted up to more than 500 kg N ha^{-1} yr^{-1}. Model calculations indicate a much smaller net N mineralization after ploughing of young grasslands (<

5 years), i.e. less than 250 kg N ha^{-1} yr^{-1}. Results of soil incubation studies in which potential N mineralization rates are measurend in disturbed soil samples taken at one moment are difficult to translate in annual actual mineralization rates in the field on a hectare basis.

Nitrogen supply

Fertilizer N recommendation for grasslands in the Netherlands account for the N supply of the soil. The soil N supply reflects the age of the sward and the accumulation of soil organic N. The N supply of mineral soils range from 50 to 300 kg per ha per year and that of peat soils from 230 to 300 kg N per ha, depending on the total amount of N in the soil, soil texture and groundwater level. Reseeding of grassland in spring provides more N to the new sward than reseeding in autumn during the first year of its establishment.

Nitrogen losses

There are indications that N leaching and denitrification losses increases with ageing of grassland. There are also indications that reseeding of grassland and conversion of grassland into arable land will be accompanied by a temporary N loss, though experimental results to sustain this view and to indicate the magnitude and pathway of the losses are lacking. The time between cultivation and reseeding of grassland is a crucial factor controlling the N leaching. Losses of N increase when the time between cultivation and reseeding increases, especially in autumn. Cultivation and directly reseeding minimizes the risk of N losses, because the new sward rapidly absorbs the mineralized N. A study carried out in the UK showed that nitrate leaching after cultivation of swards of 2, 5 or 50 years in spring was similar to that of undisturbed grassland. However, high leaching (>100 kg N ha^{-1} yr^{-1}) losses were found after cultivation of grassland to fallow or arable land. Soluble organic N content may also strongly increase after ploughing of grassland. Soluble organic N may be a pathway of NO_3 pollution of ground and surface water, because it may leach from soils and be nitrified in these waters. It is concluded that the risk in N losses from cultivated grassland (both permanent grassland and temporal grassland in rotation with arable crops) increases when

- the time between cultivation and reseeding grasland or sowing arable crop increases;
- the N uptake capacity of the preceeding crop (including a cover crop) is small, i.e. the total N uptake and the period of N uptake;
- the age of the grasland is high.

Thus, smallest risks on N losses occur when relatively young grassland is cultivated and directly reseeded in spring and the largest risk when old grassland is ploughed and left fallow for a certain period.

Gaps in knowlegde and suggestion for further research

In the Netherlands, only a few studies have been carried out on the effects of grassland cultivation on N. Quantification of the effects of cultivation on N losses via leaching and denitrification under Dutch conditions is especially lacking. The major research topics around the effects of grassland cultivation on N accumulation and losses in the Netherlands are:

- Quantification of the effects of soil type on N accumulation and N losses;
- Quantification of the changes in organic N contents of grassland soils with different cultivation systems in long-term experiments;
- To test the hypothesis that cultivation and direct reseeding of grassland in spring and early summer does not increase N losses via nitrate leaching and denitrification in comparison to undisturbed grassland;
- To test the hypothesis that the ratio between nitrate leaching and denitrification losses in sandy soils decrease during ageing of grassland;
- Quantification of N losses via leaching of dissolved organic N to ground and surface waters after grassland cultivation, because this is a potential important pathway of N loss but poorly quantified;
- Quantitative knowledge about effects of nutrient and crop management in order to minimize risk on N losses after grassland cultivation, i.e. adjustment of N fertilizer application, application of other nutrients, grazing and mowing frequency and intensity, water management, and pest control;
- Risk assessment to determine periods of high risk on N losses after grassland cultivation, using weather, soil and crop data;
- Development and testing of soil indicators that provide information on the risk of N losses when reseeding. These type of indicators may be required if legislation or restrictions around grassland cultivation are implied.

It is recommended to set-up long-term field experiments with a statistically sound design at different locations (e.g. soil type, grassland age) in which different treatments (renovation systems, grassland-arable crop rotations, N fertilizer application, time of ploughing and reseeding) are compared and in which the major N processes and the performance of the crops (yield, N content, crop quality) at the same time are quantified. Only by such integral studies it is possible to quantify the different N processes during ageing and after cultivation of grasslands and to derive management measures in order to decrease N losses to the environment. Ideally, in these studies also effects on phosphorus (P) and carbon (C) flows in the soils are quantified, because of their role in eutrophication and greenhouse gas emission, respectively.

From January 2002, a large research programme on cultivation of permanent and temporal grasslands starts (2002-2005) in the Netherlands financed by the Ministry of Agriculture, Nature Management and Fisheries. The programme addresses a large part of the mentioned suggestions for further research and includes both system analyses and field experiments. This programme aims at obtaining insight in the effects of cultivation on N and P emissions to the environment and the development of measures and tools for farmers and policy in order to achieve environmental and agricultural sound systems of permanent and temporal grasslands.

1 Introduction

The total area of grassland in The Netherlands is 1 million ha and is decreasing, because of the need of land for road construction, urban and industrial activities, recreation, nature and for forest. All grasslands are managed grasslands, used for the production of fodder for especially dairy cows. Almost all grassland (95%) is permanent (perennial) grassland, used continuously as grassland. However, once in about 5 to 10 years, the grass sward is renewed. Then, the grassland is reseeded with higher yielding grass species, after some soil cultivation and, possibly, leveling. Sometimes grassland is ploughed and converted into arable land and after some years the arable land can be converted again into grassland. In the Netherlands about 100000 ha land is anually cultivated for reseeding or for conversion into arable land (Vellinga et al., 2000).

In perennial grassland soils, there is a large turn-over of carbon (C) and nitrogen (N). Organic carbon enters the soil via senescence of roots, stubble, root exudates and grass tops via deposition of dung and urine from grazing animals and via addition of animal manure. Nitrogen (N) enters the soil via additions of N fertilizers and animal manure, and via atmospheric deposition, biological N fixation and excretion of urine and dung from grazing animals. Mineral N (NH_4 and NO_3) is taken up from the soil by active roots and converted into organic N in roots, stubble and grass during the growing season. In the soil, micro-organisms convert part of the organic C and N into carbon dioxide (CO_2) and mineral N by respiration, mineralization, and nitrification processes (see text box at end of this chapter for definitions of N processes). The other part is immobilised in the soil and accumulated as soil organic C and N. The balance between the total input into the soil and the total output via respiration and mineralisation processes determines the net accumulation of organic C and N in the soil. The accumulation of C and N vanishes because the rate of mineralization increase with time, until an equilibrium has been reached where the total input of organic C and N balances the total output via respiration and mineralization. Cultivation of grassland soil when grassland is renewed or converted into arable land enhances respiration and N mineralization (figure 1). The N content will decrease until an equilibrium in the arable situation is reached (figure 1). The N losses via leaching and denitrification may increase after ploughing of grassland when the N mineralization exceeds the N uptake capacity of the crop.

This report presents results of a literature study on the effects of ageing and ploughing of grassland on the N accumulation, N mineralization, N losses via leaching and denitrification, and soil N supply in grassland soils. The focus of the study is on experimental research in the Netherlands, but relevant studies of other countries and model calculations are also presented.

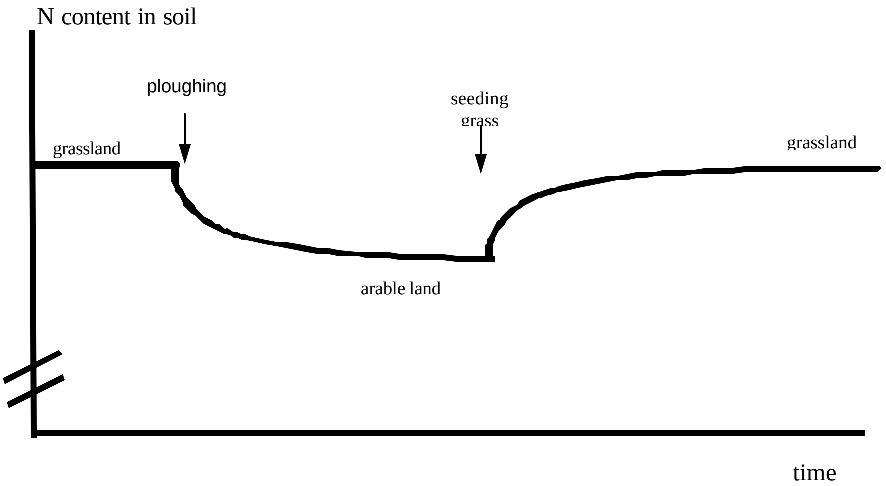

Figure 1. Schematic representation of the time course of the organic N content after ploughing of grassland and conversion into arable land (After Janssen et al., 1990).

The aims of the study were:

- to quantify the increase in the amount of soil organic N in grasslands with time (Chapter 2);
- to quantify the effects of ageing and ploughing on mineralization from soil organic N in grasslands (Chapter 3);
- to quantify the effects of ageing of grassland on N losses via N leaching and denitrification (Chapter 4);
- to quantify the effects of ageing and ploughing on the N supply from soil organic N in grasslands (Chapter 5);
- to integrate the results and to indicate the gaps in knowledge (Chapter 6).

The study was carried out in response to questions from the Ministry of Agriculture, Nature Management and Fisheries (LNV) about N losses in permanent and temporary grassland systems. The ultimate goal of the Ministry is to set up Best Management Practices to minimise N losses and other unwanted environmental effects associated with grassland management (and reseeding).

Definitions of terms used in the present study:

- Nitrogen: N
- Mineral nitrogen: ammonium (NH_4) and nitrate (NO_3)
- Organic nitrogen: nitrogen bound to organic matter
- Nitrogen accumulation in grasslands: accumulation of N in stubbles, living (and dead) roots and soil organic matter
- Nitrogen mineralization: micriobial transformation of organic N into mineral N
- Nitrogen immobilization: microbial transformation of mineral into organic N
- Net nitrogen mineralization: difference between mineralization and immobilization
- Nitrification: microbial transformation of ammonium into nitrate
- Denitrification: microbial transformation of nitrate into the gases dinitrogen (N_2) and nitrous oxide (N_2O)
- Nitrate leaching: transport of nitrate to deeper soil layers, groundwater or surface water
- Nitrogen supply: the N uptake by the harvested aboveground dry matter of unfertilized grassland

2 Nitrogen accumulation in grassland soils

2.1 Experimental methods

Nitrogen accumulation in grassland soils can be divided in accumulation of N in soil organic matter, living crop (stubbles and roots) and dead crop residues. The N accumulation in soils is usually estimated on the basis of the increase in total N contents of the soil. Soil samples are taken from the fields and the total N content in the soil is determined a number of times. Often part of the dead and living roots are removed before analysis, as roots are not considered as soil. This method is not sensitive, because of both the relatively high spatial variability in the field and the inaccuracy of the total N determination. Therefore, small changes in soil organic N cannot be detected accurately. Moreover, the bulk density of the soil also changes during ageing (especially in the top soil), which hampers the translation of N contents in g per kg to N amounts in kg C and N per ha (Hoogerkamp, 1973a). Evidently, accurate estimation of changes in total N (and C) contents can only be obtained from long-term field experiments (e.g. Jenkinson, 1988).

In several studies a division has been made in stubble, litter, soil organic matter, living roots and dead roots (sometimes mentioned as macro-organic matter (e.g. Whitehead et al., 1990). Removing living and dead roots from soils is very difficult and the results may strongly differ between the methods. Sometimes the roots are rinsed from the soil with water by which soluble organic N may be lost. Moreover, the definition of the different fractions is not clear and the size of the different fractions may change during a year. For example, Hassink (1995) showed that the a large part of the living roots in spring was recovered as macro-organic matter in autumn. These methodological differences hamper the comparison of results of studies in which N amounts are determined in in different fractions.

2.2 Literature results

The accumulation of organic matter starts soon after establishment of the grass, has no distinct lag phase, shows an asymptotic trend and may continue for more than 30 to 100 years (Hoogerkamp, 1984; 1973a). The rate and duration of the accumulation of organic matter in grassland soils strongly depends on the initial soil organic C and N contents, as indicated in figure 2. This figure shows that there was no detectable accumulation of organic N in an old grassland soil and that the N accumulation in young grassland with a low initial organic N content was higher than that in a young grassland with relatively high initial organic N content. Long-term field experiments in the UK indicate that accumulation of organic N in grassland soil may continue for more than 100 years (Jenkinson, 1988). In permanent grasslands, the accumulation of N mainly occurs in the upper 0-10 cm. After ploughing of grassland soils, the N content of the subsoil (10-30 cm) increases due to burial of organic N-rich top soil in the sub soil and some mixing with the top soil.

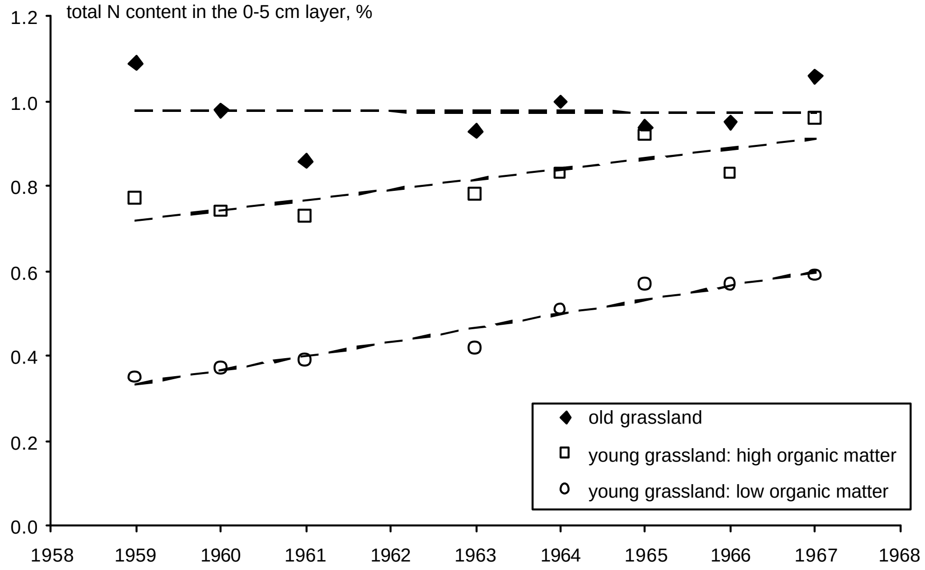

Figure 2. Time course of total N content in the 0-5 cm layer of old grassland and young grasslands with different organic matter contents on a heavy clay soil (Hoogerkamp, 1984; 1973b).

Early studies in the Netherlands indicated that the total amounts of organic matter and organic N in young grassland soil increased annually by 1880 – 2300 kg organic matter and 90-115 kg N per ha (‘t Hart, 1950), 7500 – 12900 organic matter and 215-375 kg N per ha, (Wisselink, 1961) and 2500 organic matter and 150 kg N per ha, respectively (Grootenhuis, 1961). Hoogerkamp (1984) calculated an increase of 130 kg N per ha per year during 11 years in a grassland on a clay soil and 72-98 kg N per ha per year over a 7-year period in a grassland on sandy soil.

Similar results are presented in Table 1, based on a compilation of various data by Hoogerkamp (1973a). The annual N accumulation in young grasslands on clay soils ranged from 63 to 119 kg N per ha and in sandy soils from 16 to 70 kg N per ha. The N accumulation in soil layers deeper than 5 cm were small. The N accumulation in old grasslands were smaller than that in younger grasslands.

Hassink (1994) examined the effects of age of grassland on the organic C and N contents and N and C mineralization rates (Table 2). Both total N and C contents and the N and C mineralization rates increased with ageing of the grassland. The C/N-ratio of the organic matter decreased during ageing of the grassland, suggesting that relatively more N than C is accumulated during ageing of grassland soils. The average nitrogen accumulation during the 10-yr period was approximately 130 kg N per ha per year in both the loamy and sandy soils.

Ageing of grasslands does also result in an increase of the amounts of N in roots and stubbles of the grassland (Figure 3). Van Dijk et al. (1996) showed that the amounts of N in roots and stubble of grassland of 3-6 years was 30-40 kg N per ha larger than that of grassland of 2 years old. This increase was caused by a larger amount of N in the roots; the amount of N in the stubble did not increase. The amount of N in the roots only slightly increased with increasing N application rate of grassland. The results of Van Dijk et al. (1996) indicate that the amount of N in roots increased by about 20-30 kg N per ha per year during the first 5 years of newly established grasslands on land previously used for arable land.

Studies of Hoogerkamp (1973a), Hassink and Neeteson (1991), Hassink (1994), and Ryden (1984) indicate that the level of N fertilization does not affect the amounts of C and N in grassland soils. Ryden (1984) suggested that the the input of organic C is the most limiting factor in the accumulation of organic matter and organic N in grasslands. Whitehead et al. (1990) showed that increasing the amount of applied N increased the N amount in stubble and roots (Table 5). Grazed grasslands had a larger N and C accumulation than mown grassland in a study by Hassink and Neeteson (1991). In an other study by Hassink (1994) the N and C accumulation tended to be higher in grazed grasslands than in mown grassland on sandy soils, but there was no effect of grazing on N and C accumulation in loamy soils. Drainage decreases the accumulation rate (Hoogerkamp, 1973a).

Grassland renovation leads to a temporary decrease in the amounts of soil organic C and N, mainly because of increased mineralization following soil cultivation, and the temporary stop in grass production (Jenkinson, 1987). Total net decrease in organic C and N following grassland renovation in the Netherlands are not well-known, however.

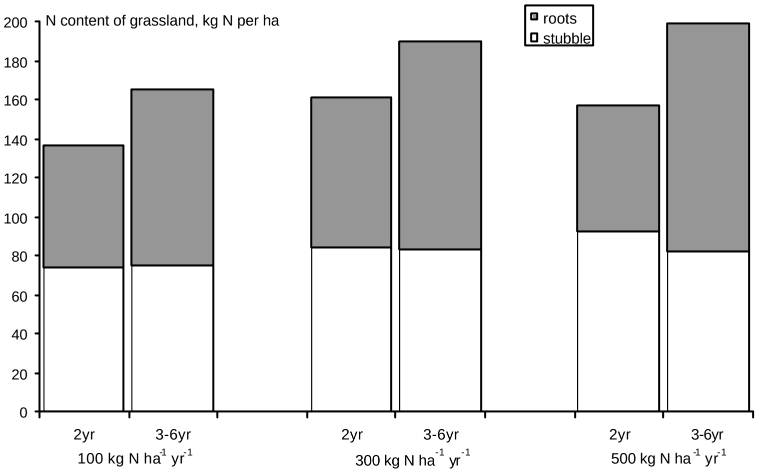

Figure 3. N contents in stubble and roots of grassland of 2 year and 3-6 years in the Netherlands (Van Dijk et al., 1996).

Table 1. N accumulation in grassland soils in the Netherlands (calculated[1] from results of Hoogerkamp, 1973b).

Soil type	grassland	layer	period years	N accumulation kg N ha^{-1} yr^{-1}
Heavy clay	old	0-5 cm	8	-13
	young	0-5 cm	8	66-105
Marine clay	young	0-5 cm	5	63-119
Sand	young	0-5 cm	6	35-47
Sand	old	0-5 cm	3	58
	young	0-5 cm	3	58-70
Peat soil with yellow sand cover	young	0-5 cm	9	16-19
Sandy clay	young	0-5 cm	5	28-35
		5-10 cm	5	<10
		10-15 cm	5	<10
		15-20 cm	5	<10

[1] assumptions: i) a linear increase/decrease in N content during the period of investigation, and
ii) bulk density 0-5 cm layer: 0.70 kg dm^{-3} and other layers 1 kg dm^{-3}

Table 2. Soil organic C and N contents, C:N ratios of the soil organic matter and C and N mineralization rates in the top 0-10 cm layer of 1-, 3- and 10-yr old grassland soils in the Netherlands (Hassink, 1994).

Soil	Age	Organic			Mineralization rate	
	years	N, %	C, %	C/N	N, mg kg^{-1} day^{-1}	C, mg kg^{-1} day^{-1}
Loam	1	0.18	2.14	12.1	1.14	19.04
	3	0.21	2.49	11.7	1.09	20.80
	10	0.28*	3.15*	11.1*	1.76*	28.16*
Sand	1	0.08	1.74	21.8	0.48	6.31
	3	0.09	1.87	20.1	0.56	6.11
	10	0.17*	2.96*	17.1*	1.31*	11.44*

* Differences between old grassland (10 years) and young grassland (1-3 years) are statistically significant ($p < 0.05$)

In a study in the UK by Cuttle and Scholefield (1995), the annual increase in N content amounted to 86 to 121 kg N ha^{-1} $year^{-1}$ during the first 5 years after ploughing and reseeding grassland.

The N contents of crop residues of grass-only and grass-clover swards were determined in a study by Davies et al. (2001) in the UK (table 3). The N content in plant tops (stubbles) was somewhat lower than those found by Van Dijk et al. (1996; figure 2): 37-43 kg N ha^{-1}. The N contents of macro organic matter in the soil was much higher (223-269 kg N ha^{-1}) than the N in the roots in the study of Van Dijk et al. (1996). This difference can be attributed to the fact that the macro-organic matter of Davies et al. (2001) also contained dead roots. The results of Davies et al. (2001) showed higher N content in the grass-only sward than in the grass-clover sward (table 3).

Tyson et al. (1990) showed an increase of C content from 1.2 tot 1.8 percent and of N content from 0.13 to 0.17 percent in the first 10 years after conversion of arable land into grassland, which is equivalent to an annual increase of 1000 kg C ha^{-1} and 75 kg N ha^{-1}. During the 20 years therafter, the C and N contents in the soil remained relatively constant. The C content of an arable soil at the same site decreased in 30 years from 1.2 to 0.8 percent and the N content from 0.13 to 0.10 percent, which is equivalent with an annual decrease in C of 290 kg ha^{-1} and of N of about 25 kg N ha^{-1}.

Table 3. Dry matter (DM) and N contents in sward residues of N fertilized grass and grass-clover swards of 8 years in the UK on a clay loam (Davies et al., 2001).

		Grass-only		Grass-clover	
		ton DM ha^{-1}	kg N ha^{-1}	ton DM ha^{-1}	kg N ha^{-1}
Residue	Pant tops	1.17	42.7	1.49	37.1
	MOM[*] 0-4 cm	14.31	204.6	11.96	152.1
	MOM 4-10 cm	2.16	30.3	2.13	29.7
	MOM 10-20 cm	1.50	19.3	1.81	23.3
	MOM 20-40 cm	1.19	15.3	1.37	17.7
	Total	20.33	312.1	18.77	259.9
Total N in 0-20 cm layer, %		0.21[**]		0.19[**]	

[*] Macro organic matter: contained both living and dead roots; soil was dispersed with sodium hexamexaphosphate

In Denmark, Eriksen and Jenssen (2001) measured 283 kg N ha^{-1} and 4100 kg C ha^{-1} in the roots of a grazed and fertilized grass-only sward of 3 years. The grass-clover sward of 3 years contained 156 kg N ha^{-1} and 3180 kg C ha^{-1} in the roots.

Whitehead et al. (1990) determined the organic matter and N contents in different grassland residues (Table 4). The N amounts in stubble and leaf litter were much smaller than those in the roots. It should be noted that the macro-organic matter as defined by Whitehead et al. (1990) only contained dead roots (Table 4); living roots were determined separately. By contrast, the macro-organic matter in the study of Davies et al. (2001) of table 3 contained all (dead and living) roots. This difference in definition of macro-organic matter is an example of difficulties in comparison of results from different studies.

Table 4. Organic matter (OM) and N contents in stubble, leaf litter, roots and macro-organic matter in two intensively managed grasslands in the UK (Whitehead et al., 1990).

	8 year old drained loam		15 year old imperfectly drained clay loam	
	OM kg ha^{-1}	N content kg N ha^{-1}	OM kg ha^{-1}	N content kg N ha^{-1}
Stubble (5 cm)	2950 (1131)[*]	75 (27)	3130 (1461)	61 (27)
Leaf litter[**]	700 (449)	17 (12)	303 (204)	6 (4)
Roots to 30 cm depth	13690 (3436)	293 (73)	9270 (1647)	205 (43)
Macro-organic matter to 30 cm depth[***]	5880 (1471)	151 (36)	11750 (2066)	330 (63)
Total	23000	536	24500	602
Soil organic N, including roots and macro-organic matter		7280		10290

[*] in parentheses: standard error

[**] leaf litter: organic matter on soil surface

[***] macro-organic matter: dead fibrous material, largely derived from roots, excluding living roots (dispersed with sodium hexamexaphosphate)

Whitehead et al. (1990) calculated the N amounts in different fractions of typical grass swards (table 5). The results of table 5 were based on the measured N amounts of table 4 and some additional experimental data. The results of table 5 indicate that the amount of N in the different grassland fractions and the N mineralization after ploughing of grassland increased with increasing age of sward, rate of N fertilizer application, and utilisation by grazing rather than cutting.

Table 5. Estimated amount of N in the unharvested fractions of typical grass swards with estimated amount of N mineralized during the first year after ploughing (Whitehead et al., 1990). Estimates are based on results of field experiments (table 4) and model calculations.

	Age and management*					
	1 year M, 50N	1 year M, 300N	3 years M, 300N	3 years G, 300N	8 years G, 300N	15 years G, 300N
N amount, kg N ha^{-1}						
Stubble (0-5 cm)	29	43	48	69	75	75
Litter	5	10	10	10	10	10
Roots	54	63	80	115	253	276
Macro-organic matter**	57	60	115	148	176	238
Total	145	176	253	342	514	599
Estimated N mineralization, kg N ha^{-1}	45	73	121	201	306	364

* M: mown, G: grazed; 50/300N = 50/300 kg N ha^{-1} year^{-1}

** organic matter in soil which is derived from death roots

2.3 Summary of results

- Amounts of soil organic C and N increase by about 1000 (range 500 – 12000) and 100 (range 20-350) kg per ha per year, respectively, during the first 10 to 30 years after establishment of grassland on arable land;
- The increase in organic C and N in grassland slowly vanishes after 30 to 100 years, depending on initial organic C and N contents;
- The rate of accumulation depends on the initial organic matter content, fertilizer, and manure applications and grazing intensity. However, the effects of these factors can not be quantified yet due to lack of data;
- The accumulation is larger on clay soil than on sandy soil, but an accurate quantification of the effect of soil type can not be made yet;
- The amount of N in roots and stubble in young grassland increase by 20-30 kg N per ha per year during the first five years;
- The (temporary) decrease in the contents of soil organic matter and N following grassland renovation has not been quantified yet;
- Management and environmental factors that influence the decrease in the contents of soil organic matter and N following conversion of grassland into arable land are not well quantified;
- Studies from literature are often difficult to compare due to differences in set-up, methodology and definition of N fractions in soil, living crop and crop residues.

3 Net nitrogen mineralization in grassland soils

3.1 Experimental methods

Predicting net N mineralization in soils is one of the most difficult and challenging tasks in N research. It is difficult because of the complex composition of soil organic matter and N, the diverse and changing microbial community in soils, the unpredictable weather conditions and the effects of climate on the microbial community. At the same time it is a great challenge because accurate estimates of N mineralization will contribute to a better prediction of N fertilizer (and manure) needs, and hence to lower N losses.

There is a wide variety of methods for estimating net N mineralization in grassland soils (e.g. Whitmore, 1999; Jarvis and Oenema, 2000). These methods include measurement of net mineralization rates in incubation studies (potential mineralization rates), in pot experiments with a crop, field incubation studies and rapid biological and chemical indices. The results of incubations can often not directly be translated to net N mineralization in the fields.

The net N mineralization in the soil is also estimated from the N uptake by the crop, and especially the harvested part of the crop. This N uptake is often mentioned as the "*N supply of a soil*". However, the N supply of soils is not only determined by the net N mineralization, but also by N losses, N uptake by roots, N immobilization in the soil and atmospheric N deposition. Results of the N supply of grasslands and the effects of ageing and ploughing on N supply are presented in Chapter 5.

Different methods yield different results, and this complicates the comparison of results between different studies. Therefore, this chapter only provides an overview of the various results obtained, without attempting to explain differences between the different studies.

3.2 Literature results

Results of laboratory incubation studies by Hassink (1994) indicate that net N en C mineralization rates increases with the age of the managed grasslands (Table 2). The rate of increase of C mineralization tended to be smaller than the rate of N mineralization. Net mineralization of N increased in 10 years by a factor of 1.5 for the loam soil and by a factor of 2.7 for the sand soil.

Hassink (1995) calculated on the basis of literature results that the annual mean net N mineralization amounts to approximately 178 kg N per ha in intensively managed permanent (old) grasslands in which the organic matter pool is in equilibrium.

Kemmers and Jansen (1985) calculated on basis of frequent measurements of net mineralization rates in the field of extensively managed grasslands in the Netherlands an annual net N mineralization rate ranging from 68 to 214 kg N ha^{-1} yr^{-1}.

Measurements in the field by Corré (2000) showed no clear effect of grassland age on net mineralization rates (Table 6). However, the number of measurements were rather small and the variation large, as follows from the large standard deviation (10 to 30 % of the mean). The conversion of grassland into arable land was accompanied with a steady decrease in mineralization since the break-up of the grassland. During the first few years after the conversion, the net mineralization tended to decrease with 100 kg per ha per year (Table 5). The large variation in the net N mineralization was related to inter annual variations in weather conditions, variations in management (e.g. type of winter crop) and to uncertainties in the experimental methods.

Van Dijk et al. (1996) measured the mineralization rate in crop rotations of grassland and arable land and in permanent maize land. Net mineralization in the 0-30 cm soil layer of maize land laid down on ploughed down 2 year old grassland was a factor of 1.2 to 1.5 higher than in permanent maize land (Table 7). Application of N fertilizer only slightly affected net N-mineralization. There were no differences between treatments in the soil layer 30-60 cm.

Table 6. Rate of net N mineralization in sandy soils at the experimental farm De Marke in the Netherlands (Corré, 2000). N mineralization was measured in the field using undisturbed soil columns incubated in tubes the field.

Crop	N mineralization, kg N ha^{-1} yr^{-1}		
	n*	Average	sd.
Permanent grassland	11	414	143
Temporal grassland: 1 yr	4	356	160
Temporal grassland: 2 yr	4	497	66
Temporal grassland: >3 yr	2	626	177
Fodder crop: 1 yr	4	372	42
Fodder crop: 2 yr	4	242	98
Fodder crop: > 3 yr	9	158	36

* number of measurements dependent on number of years (6) and experimental sites (7)

Table 7. Net mineralization in mg N per kg soil per day during 12 weeks of incubation of soil samples taken in early summer of 1989 at 20°C (Van Dijk et al., 1996).

Crop	N-application kg N ha^{-1}	Soil layer 0-30 cm	Soil layer 30-60 cm
Permanent maize	30	0.27	0.12
	170	0.25	0.11
First yr maize afer 2 yrs grassland	30	0.32	0.13
	170	0.38	0.12

Hoogerkamp (1973b) showed that the N mineralization rates in both old and young grassland soils strongly decreased with increasing depth (Table 8). Rates of N mineralization in the 0-10 cm and 10-20 cm layers of an old grassland were a factor 2.9 and 2.3 higher than that of a young grassland, respectively. This large difference was related to the differences in organic matter contents of the top soils. Comparison of tables 7 and 8 indicate a much larger N mineralization in grasslands than in maize land.

Table 8. Net mineralization rates in different layers in old grassland and young grassland (Hoogerkamp, 1973b).

Grassland	Layer, cm	Mineralization rate mg N kg^{-1} day^{-1}
Old grassland	0-10	2.50
	10-20	0.71
Young grassland	0-10	0.86
	10-20	0.31

Huntjes (1971a&b) showed that the presence of plants had a negative effect on the net mineralization rate in soil samples of permanent grassland, using ^{15}N labeling techniques. This immobilisation was attributed to excretion of C-rich organic compounds by roots and by dead roots. The immobilization of added nitrogen was much larger in permanent grassland soils than in arable soil. The study showed that after killing the roots, the recently immobilized nitrogen was more rapidly mineralized than the ‘older’ soil organic nitrogen. About 12 percent of fertilizer N added to a resown grassland was immobilized in the soil organic matter during the first month after N application. Huntjes (1971a&b) concluded that the continuous presence of plants is responsible for the accumulation of organic nitrogen in permanent pastures.

Velthof and Oenema (2001) showed that net N mineralization in mineral soils was larger in bare soil than in soil overgrown with grass (Figure 3). Apparently, nitrogen is rapidly immobilized in soil micro-organisms and soil organic matter following the establishment of a grass sod, especially in the rooting zone. These results are in agreement with those of Huntjes (1971a&b) and Hoogerkamp (1984) and show that (re)seeding of grass results in a rapid immobilization of added fertilizer N or mineralized N.

The net N mineralization under grassland on peat soil from which the grass residues were removed amounted to 1.78-2.00 mg N kg^{-1} day^{-1} (Table 9). This was a factor 2 to 8 higher than in mineral soils (Velthof & Oenema, 2001).

There are various studies (Hassink, 1994, Hoogerkamp, 1973b, Van Dijk et al., 1996, Velthof and Oenema, 2001) in which the net N mineralization rate has been determined using incubation of soil samples from grassland soils (potential net N mineralization). Comparison of these incubation studies indicate:

ii) net N-mineralization is much larger in 0-10 cm layer much larger than in 0-20 cm layer in mineral soils (Tables 7 and 8);
iii) net N-mineralization rates in the 0-10 cm layer of mineral soils increase in the order maize land < young grasland < old grasland;
iv) net N-mineralization of grassland soils increases during ageing with a factor of about 1.5 to 3 (Tables 2 and 8);

The mineralization rates derived from incuabtion studies are often expressed in mg N kg^{-1} day^{-1}. These data can not be translated to a whole year, because samples are only taken at one time. In these studies soil is often sieved to remove roots. This affect the results of the incubation study.

Table 9. Net N mineralization and N uptake from two soil layers of a peat soil used as grassland in the Netherlands. The incubation was carried out with soil from which crop residues (stubbles and roots) were removed (Velthof and Oenema, 2001).

	Total N	Organic C	C/N	Potential N-mineralization rate*	N-uptake**, mg kg^{-1}		
	g kg^{-1}	g kg^{-1}		mg N kg^{-1} day^{-1}	tops	roots	total
Vlietpolder 0-10 cm	7.7	102	13	1.78	186	83	269
Vlietpolder 10-18 cm	6.4	91	14	2.00	122	76	199

* incubated at 20 °C a during 8 weeks

** during a growing period of 10 weeks

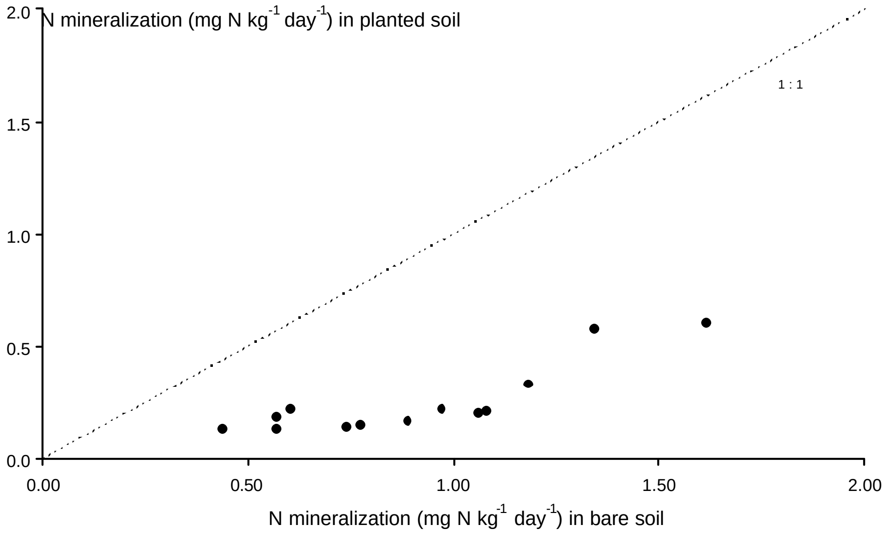

Figure 4. Effect of growing grass on the net N mineralization rate in mineral soils in the Netherlands (Velthof and Oenema, 2001). The N-mineralization was determined by incubation of soil in incubation bags for 8 weeks (results on X-axis) and from N uptake by ryegrass in a pot experiment of 10 weeks (results of Y-axis).

The study of Gill et al. (1995) in the UK showed that the net N mineralization in old grassland (> 40 years) ranged from 135 to 376 kg N ha^{-1} year^{-1}, depending on the N fertilizer application and drainage (table 10). They also showed that application of N fertilizer to a previously unfertilized grassland strongly increased net N mineralization, but there was no immediate effect of withholding fertilizer on the N mineralization. The total C and N contents were not affected by the N treatment

Patra et al. (1999) showed that net N mineralization in undisturbed grassland in UK was highest in the top soil (0.6 kg N ha^{-1} day^{-1} in May and 2.60 kg N ha^{-1} day^{-1} in August for the 0-10 cm layer) and strongly decreased with depth (< 0.5 kg N ha^{-1} day^{-1} in May and August for the 10-20, 20-30, and 30-40 cm depths). The net N mineralization in a ploughed (to 10 cm depth) and reseeded grassland was similar in all layers; about 0.4 kg N ha^{-1} day^{-1} in May and 0.4-0.7 kg N ha^{-1} day^{-1} in August). These results showed that ploughing of grassland results in a strong decrease in N mineralization of the upper few cm and a slight increase of the N mineralization in the deeper layers (10-40 cm). This effect is caused by mixing the top soil with the sub soil during ploughing and soil cultivation.

Davies et al. (2001) measured a release of 449 kg N ha^{-1} and 244 kg N ha^{-1} during a 18-months fallow period after ploughing a grassland sward and a grass-clover sward, respectively. The net effect of cultivation on grass N uptake when grass was resown was 85 kg N ha^{-1} for grass-clover and 140 kg N ha^{-1} for grass-only swards over 18 months, compared to continued unfertilized grassland.

Other studies in the UK showed similar net N mineralization rates of 300 to 500 kg N ha^{-1} $year^{-1}$ after ploughing old grasslands (> 30 years) (Ryden et al., 1984; Whitmore et al., 1992).

In several studies, net N mineralization after ploughing of grassland to arable land has been calculated using models (Catalan and Janssen, 1990; Davies et al., 2001; Vellinga et al., 2000; Velthof et al., 2000; Whitmore et al., 1992; Whitehead et al., 1990). Model calculations of Velthof et al. (2000) indicate net N mineralization rates of 174 kg N ha^{-1} $year^{-1}$ after ploughing of grassland of 5 years to 265 kg N ha^{-1} $year^{-1}$ after ploughing of grasslands of 15 years old (table 10). The net N mineralization strongly decreased in the years thereafter. Differences between studies in input parameters hamper a good comparison of the studies. For example, in the study of Whitehead only the crop residues (including macro-organic matter) are accounted for, but not the (remaining) soil organic matter. In the study of Catalan and Janssen (1990) the N in stubble is not accounted for. There are also differences between the studies in the assumed C : N ratio in the different fractions. Reseeding of grassland leads to N immobilisation after an initial net mineralization. This is often not accounted for in models (e.g. table 10).

Table 10.Calculated net N mineralization from grassland-derived organic matter” after conversion grassland of 5, 10, and 15 years into arable land (Velthof et al., 2000).

Years after conversion	N mineralization, kg N ha^{-1} $year^{-1}$		
	5 years	10 years	15 years
1	174	231	265
2	60	90	104
3	28	43	51
4	16	25	30
5	10	16	19

3.3 Summary of results

- The rate of net N mineralization in grasslands soil tend to increase with the age of the grassland by a factor 1.3 to 2.9 in 10 years;
- The rate of net N mineralization decreases rapidly with soil depth; the top 5 cm has by far the highest mineralization;

- Ploughing results in a turn-over of the top 20-30 cm, and a decrease in N mineralization in the upper few cm's;
- Estimated rates of net N mineralization in grassland soil vary widely because of environmental differences (soil type, drainage) and differences in definitions, methods and procedures for estimating mineralization;
- The effect of soil type on net N mineralization during ageing and after ploughing of grasslands is not yet well-quantified
- Results of net N mineralization rates determined by soil incubation studies of several are difficult to translate in mineralization rates in kg N ha^{-1} $year^{-1}$.
- Rates of net N mineralization are larger in grassland soil than in arable soil. N mineralization decreases rapidly following the conversion of grassland into arable land.
- Reseeding of grassland will be accompanied by a temporary loss of C and N, though experimental results to sustain this view and to indicate the magnitude and pathway of the losses are lacking.
- Models are useful tools to estimate net N mineralization after ploughing of grassland, but differences between studies in input parameters (e.g. C and N amounts in the different fraction) hampers the comparison of these studies.
- There is a need for a standardized set of methods for quantification of net N mineralization.

4 Nitrogen losses via leaching and denitrification

4.1 Experimental methods

There are many methods for measuring NO_3 leaching from grassland soils (e.g. Jarvis and Oenema, 2000). Most methods are based on the measurement of the NO_3 concentration in the soil solution (e.g. by cups or sampling tubes), groundwater or drainage water and multiplying this concentration with the measured or calculated volume of percolated water. Differences in sampling method, depth of sampling, time of sampling, and calculation or measurement of water flow may all affect the calculated NO_3 leaching.

Measurements of actual and potential denitrification losses from soils are mostly based on the acetylene inhibition technique (Ryden and Dawson, 1982). Differences in sampling strategies in space, depth and time and the method of incubation may all affect the calculated denitrification loss.

Different methods yield different results, and this complicates the comparison of results between different studies. This chapter section provides an overview of the various results of N losses obtained in the different studies, without attempting to explain differences between the different studies in full.

4.2 Literature results

4.2.1 Effects of ageing on N losses

Denitrification is carried out by heterotrophic bacteria, i.e. bacteria that require organic C compounds as substrate. Losses of N via denitrification depend heavily of the amounts of degradable organic matter in the soil, soil wetness and on the amounts of nitrate. Results presented in Figure 5 indicate that the potential rate of denitrification is linearly related to the rate of C mineralization. Woldendorp (1963) showed that denitrification is stimulated by the presence of living plants, due to the release of easily available C compounds by the roots. This would suggest that the potential for denitrification increases with the age of the grassland. Whether the ratio of denitrification to nitrate leaching also increases with grassland age remains speculation.

The amount of mineral N in the soil after the growing season in autumn is usually considered to be a proper indicator for the amount of N that may be loss from the grassland system by leaching and denitrification. The larger the amount of soil mineral N in autumn, the larger the N loss. Results presented in Figure 6 indicate that the amount of soil mineral N in autumn tend to be related to the age of the sward. The older the sward, the larger the amounts of soil mineral N, irrespective of the N fertilizer application. Soil mineral N was approximately 10 kg per ha larger in the seven-year old sward compared to the one-year old sward. The effect of sward age on soil mineral N was as large as the effect of increasing the N fertilizer application from 100 – 140 kg to 380 - 500 kg per ha per year (Figure 6).

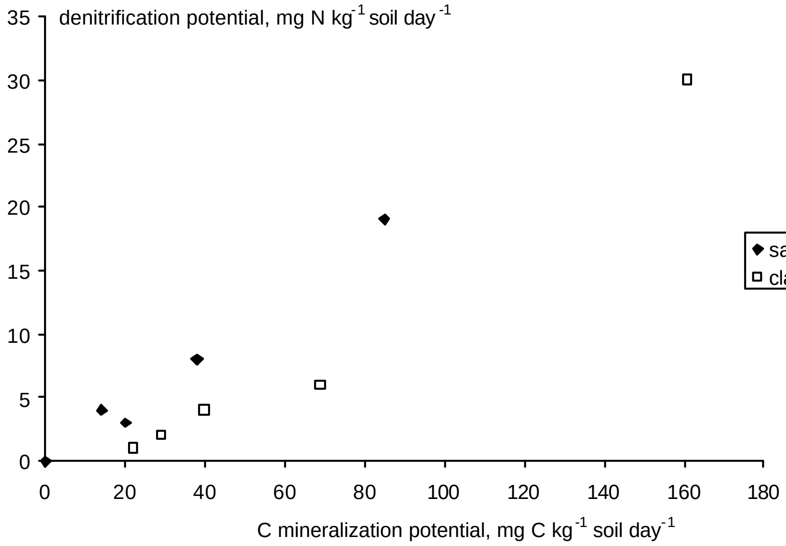

Figure 5. Relation between C mineralization potential and denitrification potential in samples of different layers of sandy and a clay grassland soils (Velthof and Oenema, 1995).

In a study of Cuttle and Scholefield (1995) it was shown that nitrate leaching from a fertilized (150-200 kg N ha^{-1}) and grazed (by lambs) sward in the UK increased with ageing from less than 10 kg N ha^{-1} for swards of 2-3 years to 25-40 kg N ha^{-1} yr^{-1} for swards of 5-7 years. The stocking rate was adjusted to the herbage production and increased from about 25 lambs ha^{-1} for swards of 2-4 years to 40-60 lambs ha^{-1} for swards of 6-7 years. The greater leaching losses from the older swards were assumed to result from increased N mineralization during ageing, less immobilisation of N fertilizer, higher stocking rates and greater returns of urine to the soil. Thus, the effect of the age of the sward on leaching losses could not be separately determined, because the stocking rate also increased with increasing sward age. Model calculations showed that the N leaching losses from the grazed grassland could be kept constant during ageing if the applied amount of N fertilizer was adjusted to the N supply of the soil through net N mineralization, i.e. the amount of N fertilizer applied was reduced from 250 kg N ha^{-1} yr^{-1} for swards of 1-2 years to 217 kg N ha^{-1} yr^{-1} for swards of 20 years.

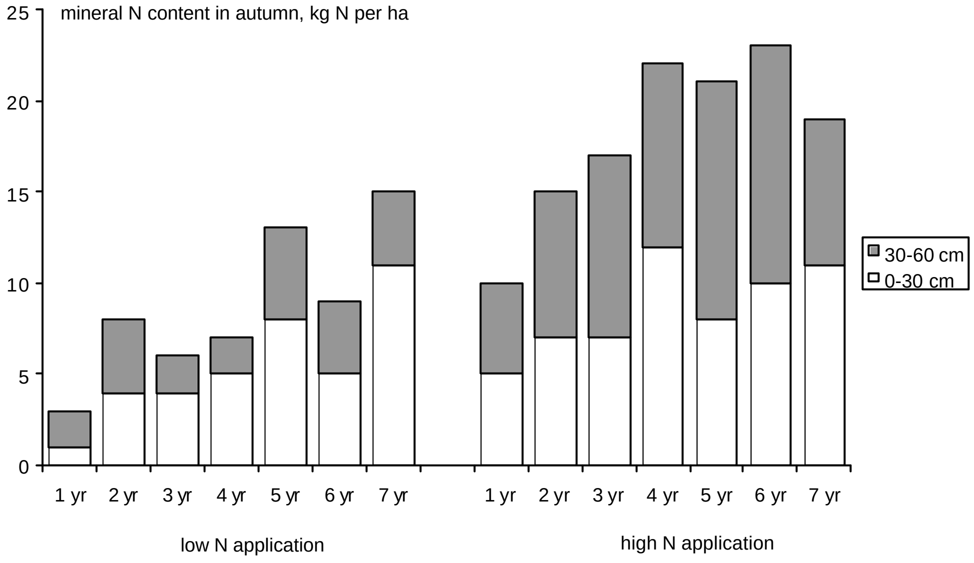

Figure 6. Soil mineral N contents (0-30 and 30 –60 cm soil depth) in grasslands of different ages on a sandy soil in autumn of 1993, just after the last cut. Low N application: 140 kg N ha^{-1} for 1st yr grassland and 100 kg N ha^{-1} for grassland of 2-7 yrs. High N application: 380 kg N ha^{-1} for 1st yr grassland and 500 kg N ha^{-1} for grassland of 2-7 yrs (Van Dijk, 1996).

4.2.2 Effects of ploughing on N losses

Ploughing and reseeding grassland in autumn increased the mineral N contents in soil within 2 months with about 40 to 100 kg N per ha (Figure 7). The mineral N contents was higher for a 8-year old sward than for a 3-year old sward. After the winter, the mineral N contents decreased with about 40 to 60 kg N per ha, probably because of immobilization by the reseeded grassland and partly because of losses via denitrification and nitrate leaching .

In a study of Van Dijk (1997) concentrations of NO_3 in drain water from a clay soil were measured from a grass-clover sward, a grass-clover sward during the first year after ploughing of grassland and maize land during the first year after plouhing up grassland. The NO_3 concentrations in drain water from maize land ranged for 50 to 200 mg NO_3 l^{-1}), those from grass-clover sward was less < 25 mg NO_3 l^{-1} and those from the reseeded grass-clover sward ranged from 20 to 50 mg NO_3 l^{-1}. The higher NO_3 concentration in the reseeded grass-clover sward in comparison to the undisturbed grass-clover sward suggests that ploughing and reseeding increased NO_3 leaching. The much lower NO_3 concentrations in the drainage water from the reseeded grass-clover sward than from the maize land suggested that the uptake of N released from ploughed grassland was much higher for grass-clover than for maize.

Average nitrate concentrations in the upper groundwater of grassland and maizeland of different ages at De Marke ranged between 33 to 76 mg l^{-1} (Table 11). There was a tendency that NO_3 concentrations in groundwater of temporal grassland decreased during ageing.

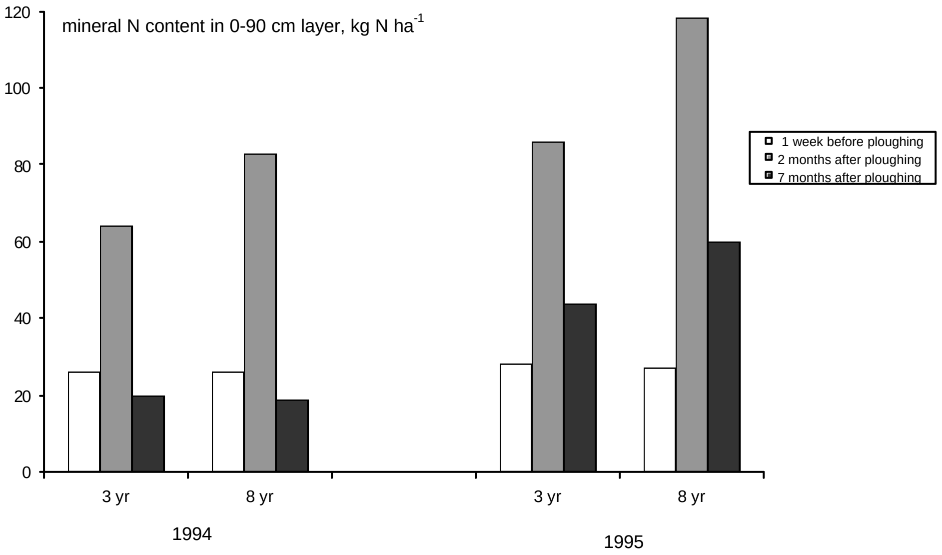

Figure 7. Soil mineral N contents in grassland of 3 and 8 years old, about 1 week before ploughing and about 2 and 7 months after ploughing in August (Praktijkonderzoek Veehouderij, 2000).

Table 11. Average NO_3 concentration in ground water in a sandy soil at De Marke in the Netherlands for different crop rotations (Conijn, 2000). The management of grassland and maizeland was focussed at high yield and low NO_3 leaching.

Crop	Average NO_3 concentration im mg l^{-1} in 1993-1998 [1]
Permanent grassland	53 (41-84)
Grassland, 1st year	76 (43-127)
Grassland, 2nd year	43 (16-66)
Grassland, >2nd year	33 (27-45)
Maize, 1st year	47 (9-177)
Maize, 2nd year	67 (13-139)
Maize, >2nd year	63 ((30-115)

[1] in parentheses: range

Table 12 presents results of a study of Davies et al. (2001) in the UK. Ploughing of grassland increased N losses via leaching, N_2O emission and denitrification when the soil was left fallow. Ploughing followed by reseeding considerably decreased the N losses, and especially those of N_2O emission and denitrification. The N leaching losses were much higher than those via N_2O emission and denitrification. This study also showed that the mineral N contents in the 0-20 cm soil layers were higher (up to about 100 kg N ha^{-1}) in the resown grassland than in the undisturbed grassland during the first year after ploughing. The mineral N contents in the 0-20 cm soil layers were higher (up to about 75 kg N ha^{-1}) in the ploughed-fallow soil than in the resown soil during the year after ploughing. It was concluded that leaving swards ungrazed and unfertilized over winter before ploughing in spring has the potential to decrease N emissions considerably.

Table 12. N losses from ploughed grassland on an imperfectly drained clay loam via nitrate leaching (NO_3), nitrous oxide emission (N_2O) and denitrification (deni) (Davies et al., 2001).

Treatment	1992-1993			1993-1994		
	NO_3	N_2O	deni	NO_3	N_2O	deni
	kg N ha^{-1}			kg N ha^{-1}		
Continued grass	0.7	0.1	0.4	1.3	0.2	0.8
Grass sward ploughed out 1992, resown to ryegrass	44.3	-	-	1.3	0.1	0.4
Grass sward ploughed out 1992, left fallow	250.6	1.5	7.8	296.3	0.5	2.7
Contunued grass-clover	3.9	0.5	1.6	1.2	0.1	0.5
Grass-clover ploughed out 1992, resown to ryegrass	49.9	-	-	0.5	0.1	0.3
Grass-clover ploughed out 1992, left fallow	106.8	3.7	17.5	197.4	0.8	4.1

Scholefield et al. (1993) showed that NO_3 leaching losses (measured in lysimeters) from permanent grassland on a clay soil receiving 400 kg N ha^{-1} were higher than the leaching losses from similarly N fertilized grasslands which had been ploughed and reseeded. Only in the first winter after ploughing, NO_3 leaching in ploughed grassland was higher than in permanent grassland. The average N leaching during 5 years after ploughing amounted to 27 kg N ha^{-1} yr^{-1} and that of unploughed permanent grassland amounted to 80 kg N ha^{-1} yr^{-1} in an undrained soil. Leaching losses were 199 kg N ha^{-1} yr^{-1} for permanent grassland and 85 kg N ha^{-1} yr^{-1} for reseeded grassland on well-drained soils. The smaller losses from the reseeded grassland was attributed to a higher immobilization of N in the reseeded sward.

The study of Adams and Jan (1999) in the UK showed that the N uptake increased and the NO_3 leaching decreased when grass-clover was immediately sown after cultivation than when sowing of grass was delayed with one month (table 13). Cultivation and sowing in October resulted in less N uptake and higher leaching losses than cultivation and sowing in August and September. The leaching losses from fallow soils were much higher than from reseeded swards.

In Denmark, Djurhuus & Olsen (1997) measured that total N leaching losses after cultivation of a one year grass/clover leys range of 160 to 254 kg N ha^{-1} during 3 years (53 to 85 kg N ha^{-1} yr^{-1}). Winter wheat did not have the potential to take up the mineralized N after ploughing of a grass/clover lay in August. The smallest leaching losses were found when the grass/clover lay was cultivated in spring in stead of in autumn.

In the UK, Johnston et al. (1994) showed that the soil mineral N contents in October increased from 126 kg N ha^{-1} for a grass/clover ley of 1 year to 252 kg N ha^{-1} for a grass/clover of 6 year, after ploughing at the end of the summer. On the basis of these experimental results, N leaching losses of 250 kg N ha^{-1} following the 6 year ley were calculated.

In New Zealand, Francis (1995) found that delaying the ploughing of a temporary leguminous grassland in New Zealand from autumn to spring decreased NO_3 leaching losses with 8 to 52 kg N ha^{-1}, depending on the rainfall pattern. Sowing cover crops in ploughed grassland reduced leaching losses up to 60 percent when sown in early autumn.

In the UK, Bhogal et al. (2000) assessed the effect of cultivation and reseeding on the fate and distribution of N in old grassland (Table 14). The measurements were carried out 10 and 14 months after cultviation The results showed an increase in mineral N and, especially soluble organic N after 10 months. After 14 months, there were no clear effects left. The most striking result is the very high contents of soluble organic N in the soils in June (11-57 mg N kg^{-1}). This soluble organic N may be mineralized in the top soil, but may also leach to deeper soil layers, groundwater or surface waters. There it can be mineralized and nitrified and this may be an important pathway of NO_3 pollution of groundwater and surface water after cultviation of grasslands. The authors concluded that measurement of soluble organic N should be included in N cycling studies in agricultural soils, so that full account may be taken of its potential as source or sink of mobile N.

Table 13. Effects of time of cultivation and sowing of a grass-clover sward on a clay loam on N uptake by reseeded grass and on NO_3 leaching in UK in two years (Adams and Jan, 1999).

Month of cultivation	Month of sowing	1994-1995		1995-1996	
		N offtake	NO_3-leaching	N offtake	NO_3-leaching
		kg N $ha^{-1}yr^{-1}$			
Aug	Aug	60	31	52	10
Aug	Sept	66	54	38	15
Aug	-	-	224	-	67
Sept	Sept	93	41	40	15
Sept	Oct	24	128	36	54
Sept	-	-	223	-	84
Oct	Oct	44	93	44	61
Oct	Nov	28	149	43	77
Oct	-	-	238	-	116

Table 14. N pools in mg N per kg soil in 0-90 cm layers in undisturbed and in cultivated (12.5 cm) and reseeded grasslands on a poorly drained clay loam (North Wyke) and silty clay loam (Rosemaund) (Bhogal et al., 2000). Grasslands were at least 50 years old.

	Rosemaund		North Wyke	
	undisturbed	reseeded	undisturbed	reseeded
June: 10 month after cultivation				
mineral N	4.5	6.8	14	17
soluble organic N	4.2	57	2.7	11
potential mineralizable N*	57	50	79	87
October: 14 months after cultivation				
mineral N	4.0	3.6	12	7.7
soluble organic N	3.4	2.9	3.0	4.1
potential mineralizable N*	10	8.1	28	38

*determined by aerobic incubation

In the UK, Lloyd (1992) measured N leaching losses to arable land after ploughing of grasslands. Cereals (winter and spring wheat and spring barley) were sown after ploughing grassland. Over the three winters, total N leaching losses were of the order of 100-120 kg N ha^{-1} for sites with a low initial N status, 250 kg N ha^{-1} for sites with a higher N status, and 1000 kg N ha^{-1} for a site with an intensively managed old grassland. At one site highest N leaching losses occurred during the first winter, but at the other sites highest leaching losses were found in the second and third winter after ploughing. There was no clear effect of timing and type of cultivation (ploughing versus minimum tillage) on N leaching losses. There was a poor relation between the mineral N in the soil in autumn and N leaching in the subsequent winter.

Shepherd et al. (2001) assessed the effects of ploughing and reseeding of grassland on nitrate leaching during winter. The amount of rainfall in winter had a much larger effect on nitrate leaching than sward age and the time of reseeding. The authors concluded that ploughing and reseeding in winter provided a large risk on nitrate leaching, but that ploughing and reseeding in spring had a little effect on N leaching in comparison to undisturbed grassland (table 15). In 95/96 reseeding increased N leaching from swards of 5 yr and 50 yr, but not from swards of 2 yr. This effects was smaller in 96/97. It should be mentioned that the N leaching after autumn ploughing increased in the order 5 yr < 2 yr < 50 yr. It is not clear whether this order is related to sward age or to other factors (e.g soil type). Other results of Shepherd et al. (2001) showed that there were no residual effects of autumn reseeding on N leaching in the second winter after cultivation; the N leaching was similar to that of undisturbed grassland

Table 15. Effects of reseeding (ploughing and resowing) on nitrate leaching below 60 cm from a freely draining silty clay loam during winters of 1995/1996, 1996/1997, 1997/1998 (Shepherd et al., 2001)[1]*.*

Sward age	Treatment	N leached, kg N ha^{-1}		
		95/96	96/97	97/98
2 yr	undisturbed	74	2	5
	autumn 1995 reseeded	66	*	*
	spring 1996 reseeded	*	10	1
	autumn 1996 reseeded	*	26	1
5 yr	undisturbed	37	0	1
	autumn 1995 reseeded	60	*	*
	spring 1996 reseeded	*	3	1
	autumn 1996 reseeded	*	10	2
> 50 yr	undisturbed	122	3	19
	autumn 1995 reseeded	173	*	*
	spring 1996 reseeded	*	5	7
	autumn 1996 reseeded	*	34	6

[1] drainage 159-186 mm in 95/96, 15-75 mm in 96/97, and 198 mm in 97/98.

4.3 Summary of results

- The amounts of soil mineral N in autumn tend to increase with the age of the grassland. A considerable part of this mineral N may be lost during winter.
- The potential for denitrification is related to potential N mineralization rate, and increases with the age of the grassland;

- Relationships between grassland age and N losses via leaching and denitrification have not been measured in the Netherlands;
- There is experimental evidence from studies abroad that indicates that large N losses may occur following the conversion of grassland to arable land, but relationships with grassland age have not been well established;
- N leaching losses and denitrification losses after ploughing of grassland has not been measured well in the Netherlands;
- Soluble organic N content may strongly increase after ploughing of grassland. Soluble organic N may be a pathway of NO_3 pollution of ground and surface water, because it may leach from soils and be nitrified in these waters;
- The time between ploughing and resowing of grassland is a crucial factor controlling the N leaching; the leaching losses increases when the time between ploughing and resowing increases, especially in late autumn;
- In the UK high leaching (>100 kg N ha^{-1} yr^{-1}) losses have been found after ploughing grassland to fallow or arable land in the UK;
- One study in the UK indicates higher N leaching losses from old permanent grassland than from young reseeded grassland during the first years after ploughing and reseeding. This is apparent anomaly is attributed to the high N immobilization in young grassland.

5 Nitrogen supply

5.1 Experimental methods

The input of organic matter into the soil via addition of animal manure and the return of grass residues, roots and stubble, not only contributes to the build up of soil organic matter but also to the supply of mineralized N to the grass crop. Here, the N supply or N supplying capacity of a grassland soil is defined as the N uptake in the harvested aboveground dry matter of unfertilized grassland (e.g. Hassink, 1995). Evidently, the total N supply is the net effect of the total sum of N 'input' by net N mineralization, atmospheric N deposition, biological N fixation and soil mineral N present at the start of the growing season, corrected for possible N losses via leaching, denitrification and ammonia volatilization. In practice, differences between soils in N supply are most often caused by differences in net N mineralization rate. The N supply is determined by harvesting the tops of the grassland several times during the growing season and analyzing the dry matter yield and N content of the tops. Sometimes the N supply is determined in a greenhouse using soil columns (e.g. Hassink, 1995; Velthof & Oenema, 2001).

5.2 Literature results

Hassink (1995) determined the N supply of different grassland soils in the field, and in the greenhouse, using soil columns. The N supply in the field was on average 144 kg N ha^{-1} for sandy soils (range: 108-175 kg N ha^{-1}), 126 kg N ha^{-1} for loamy soils (range: 67-181 kg N ha^{-1}), and 180 kg N ha^{-1} for clayey soils (151-208 kg N ha^{-1}). The greenhouse results for the sandy and loamy soils were similar to those derived from the field, but the N supply from the clayey soil was significantly higher under field conditions than in the greenhouse. This was attributed to higher denitrification losses in the greenhouse; the soil in the greenhouse experiment was more wet than under field conditions.

For peat soils, Hassink (1995) derived the relationship:

N supply = 189 + 3.1*deepest groundwater table (in cm).

Current N fertilizer recommendations for grasslands on mineral soils in the Netherlands are related to the N content of the soil and to soil texture, so as to correct for the N supply of the soil, based on the work of Hassink (1995). The grassland soils are divided in different groups of N supplying capacity. The N supplying capacity of sand and clay soil depends on organic N content and texture. For clay soil, ground water level is an additional correction factor. The N supplying capacity of peat soils only depends on groundwater level. The higher the soil N content, relative to the soil clay+silt content, the larger the N supplying capacity and the lower the recommended N fertilizer recommendation. Similarly, the shallower the mean ground water level the lower the mean N supplying capacity and the larger the N fertilizer recommendation. The maximum level of N supply for sandy soils is 200 kg N per ha (Anon., 1998). The maximum level of N supply for clay soils with a shallow groundwater level is 230 kg N per ha, and for clay soils with a deep groundwater level 300 kg N per ha. For peat soils with a shallow groundwater level, the mean N supply is 230 kg N per ha and for peat soils with a deep groundwater level 300 kg N per ha per year (Anon., 1998). Farmers calculate the recommended N application rates using the N supply tables in the fertilizer recommendation. Evidently, the N fertilizer recommendations in the Netherlands account for the N supplying capacity of the grassland soil, and hence also for the built up of organic N in old swards (i.e. old swards have higher total N contents and thus a higher N supply) .

Schothorst and Hettinga (1991) investigated the N supply of reseeded grassland after the old sward had been ploughed down. The N supply ranged from 120 to 158 kg N per ha per year during four years after ploughing of the permanent grassland (Table 16). There were no clear differences between years. The low N supply during year one is related in part to the establishment phase of the new grass sward, when much of the organic matter will be invested in the roots and stubble.

Table 16. Total N uptake in unfertilized grassland after soil cultivation and reseeding in 1976 (Schothorst and Hettinga, 1981).

Year	N uptake, kg per ha
1977	120
1978	145
1979	122
1980	158

The time of reseeding is essential for the utilization of the N liberated from the decaying ploughed down sward. This is shown by results presented in Figure 8. When reseeded in autumn, the new sward established on the ploughed down of a eight years old sward was able to take up about 15 kg N per ha more from the soil than the sward established on a three years old sward. However, when reseeded in spring, much more N could be taken up. Reseeding in spring gave 35 kg N per ha more in the herbage compared to reseeding in autumn. Figure 8 also shows that the N fertilizer input of the old sward did not have a significant effect on the amount of N that could be utilized by the newly established sward.

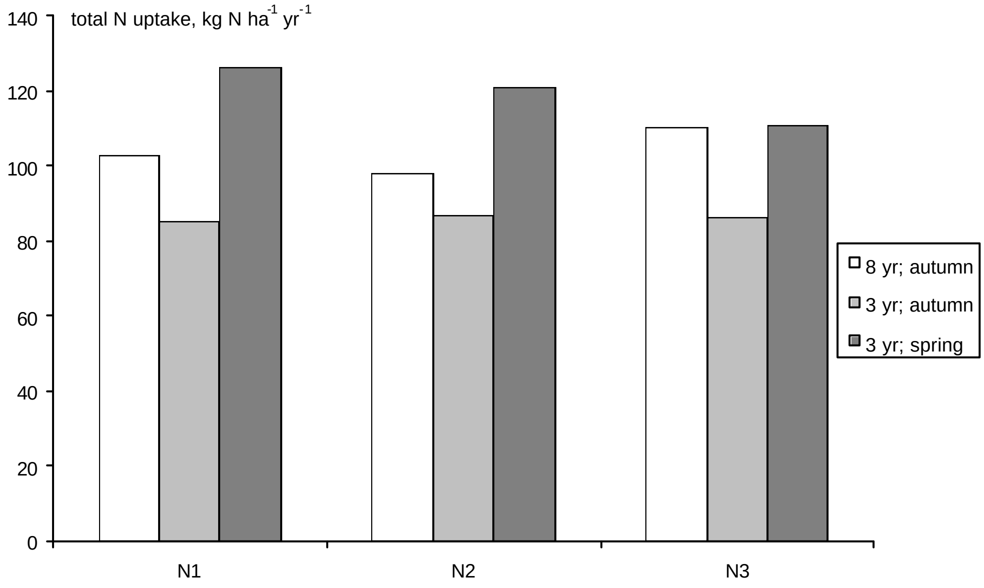

Figure 8. Total annual N uptake by reseeded unfertilized grassland after ploughing and reseeding of grassland of 3 years (in spring and autumn) and of 8 years. There were three N application rates for the grasslands that was ploughed: N1: 140 kg N ha^{-1} yr^{-1}; N2: 300 kg N ha^{-1} yr^{-1}; N3: 500 kg N ha^{-1} yr^{-1} (Praktijkonderzoek Veehouderij, in preparation).

The N supply of an old (> 40 years) grassland on clay soil in the UK was 170 kg N ha^{-1} when unfertilized in the previous 10 years and 223 kg N ha^{-1} when N fertilized with 200 kg N ha^{-1} in the previous 10 years (Gill et al., 1995).

In the UK, Davies et al. (2001) measured that the N uptake by the above ground herbage of unfertilized permanent grassland was about 175 kg N ha^{-1} and that of a ploughed and resown unfertilized grassland about 275 kg N ha^{-1} during 18 months (June 1992 – December 1993).

In the UK, Johnston et al. (1994) assessed the effects of plouging leys of different ages at the end of the summer on N uptake of the preceding crop. They showed that amount of required N fertilizer in spring in comparison to a 1 year ley decreased with 6 kg N ha^{-1} for a 2-year ley to 126 kg N ha^{-1} for a 6-year ley. The N effects on potatoes in the 2nd year and winter wheat in the 3rd year after ploughing were small, i.e. about 6 kg N ha^{-1}.

In Denmark, Eriksen and Jensen (2001) measured the N uptake of unfertilized barley after ploughing of grass-only or grass-clover swards of three years. The N uptake of barley from a ploughed grass-only sward was 120 kg N ha^{-1} (77 kg N ha^{-1} in grains and 43 kg N ha^{-1} in straw) and from a ploughed grass-clover sward was 110 kg N ha^{-1} (73 kg N ha^{-1} in grains and 37 kg N ha^{-1} in straw). The N uptake was not different for rotovation in combination with ploughing than for only ploughing of the grasslands.

5.3 Summary of results

- Fertilizer N recommendation for grasslands in the Netherlands account for the N supply of the soil; the N supply reflects the age of the sward, the accumulation of soil organic N and drainage;
- The N supply of mineral soils range from 50 to 300 kg per ha per year and that of peat soils from 230 to 300 kg N per ha, depending on the total amount of N in the soil and soil texture which combines is a measure for the age of the sward, and groundwater level.
- Reseeding of grassland in spring provides more N to the new sward than reseeding in autumn during the first year of its establishment.
- The N supply of reseeded grassland is related to the age of the old sward, but data are lacking for an accurate quantification of this N supply.

6 Synthesis and gaps in knowledge

6.1 Introduction

In the preceding chapters, a literature review is given on the N dynamics in grassland systems during ageing and following cultivation. Each chapter ends with a summary, including the important gaps in knowledge. Sofar, the research on grassland cultivation and reseeding has been fragmentary, depending on the scope and purpose of the study. Early studies only focussed on the agronomic aspects, while some of the more recent studies only focussed on a specific environmental aspects (i.e. soil mineral N or N_2O emission).

Efects of ageing and cultivation on most N processes have been studied, but the amount of data is not sufficient to accurtately quantify effects of grassland age, grassland management (time and method of cultivation and reseeding, N fertilization and grazing), soil type and groundwater level on the different N processes. In the Netherlands, only a few studies have been carried out, especially agronomic studies. A quantification of the effects of soil type, soil cultivation and grassland management on N losses via leaching and denitrification under Dutch conditions is completely lacking .

This final synthesis chapter is split into thee parts:

i) effects of soil type, groundwater regime, and weather conditions on N processes, because these factors have a strong impact on N processes;
ii) effects of grasland use and nutrient management on N processes, because these are manageable factors that have a strong impact on N processes;
iii) identification of the important gaps in knowledge and recommendations for further research.

6.2 Soil type, groundwater regime and weather conditions

6.2.1 Soil type and groundwater regime

Effects of soil type and groundwater regime on N mineralization and N losses in grassland systems are large and complex. The relative effects of the major single soil factors texture, organic matter and ground water on net mineralization, leaching and denitrification are shown in figure 9. The patterns of leaching and denitrification are complementary, while net N mineralization behaves rather independently. When soil factors and groundwater regime are combined, complex pictures emerge (not shown), especially when the groundwater regime is considered as a dynamic (i.e. changing in time) variable in reponse to weather conditions.

These factors must be understood to be able to analyze and predict effects of ploughing of grassland and reseeding on net N mineralization and N leaching properly. There are also feedbacks of grassland management ploughing of grassland on soil factors (e.g. soil organic matter, drainage, groundwater regime) and hence indirectly on net N mineralization and leaching, which further complicate the relationships between grassland management and N mineralization and leaching. Evidently, these interactive effects can only be analyzed and understood well via a combination of simulation modelling and well-focussed field experiments. These interactive effects must be understood well, to be able to understand the effects of grassland management and to be able to derive best management guidelines.

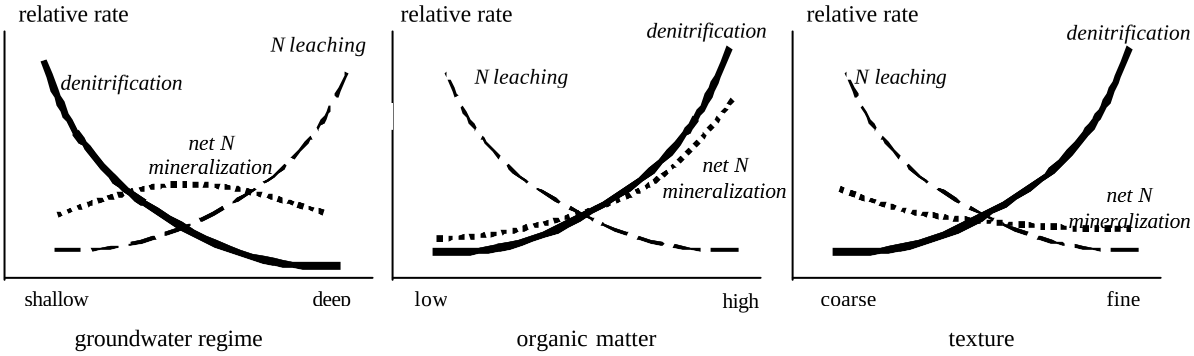

Figure 9. Schematic representation of the single effects of groundwater regime, organic matter content and texture on net N mineralization, denitrification, and N leaching.

6.2.2 Weather conditions

Temperature and rainfall strongly affect N mineralization rate, N losses via leaching and denitrification, and N uptake by the crop. The amount of rainfall during winter determines the amounts of N lost via nitrate leaching, denitrification and the residual mineral N in the soil profile in spring. Results of Shepherd et al. (2001) in table 15 showed that leaching losses were more than 100 kg N ha^{-1} larger in a relatively wet winter than in a relatively dry winter and in a very wet winter. This was probably due to the effects of rainfall on the ratio denitrification to nitrate leaching during winter. The effect of weather conditions on N losses is often much larger than that of management. These results clearly demonstrate that effects of soil type, soil cultivation, and grassland management on leaching losses should be based on long-term field experiments. Moreover, a risk assessment using weather data should be included in evaluation of systems of grassland cultivation (e.g. what is the risk on wet and mild winter, with a high leaching potential).

6.3 Grassland management and nutrient management

6.3.1 Distinguishing grassland systems

Nitrogen accumulates in the soil during ageing of grasslands (e.g figure 2). After cultivation of grassland, N mineralization increases and the risk on N losses via leaching and denitrification also increases. Four systems of grassland cultivation may be distinguished, namely

i) undisturbed permanent grassland (i.e. grassland that is never ploughed);
ii) ploughed and reseeded permanent grasslands (time of ploughing and reseeding varies from 5 to 20 years and is dependent on soil type and management);
iii) permanent grassland (>5 years) converted into permanent arable land (> 5 years), and
iv) short-time rotations with temporal grassland (< 5 years) and arable land.

The effects of these cultivation systems on N accumulation and N processes strongly differ, as schematically indicated in figure 10. The N processes and the risk on N losses in the four systems of grassland cultivation are discussed below on the basis of the results of literature.`

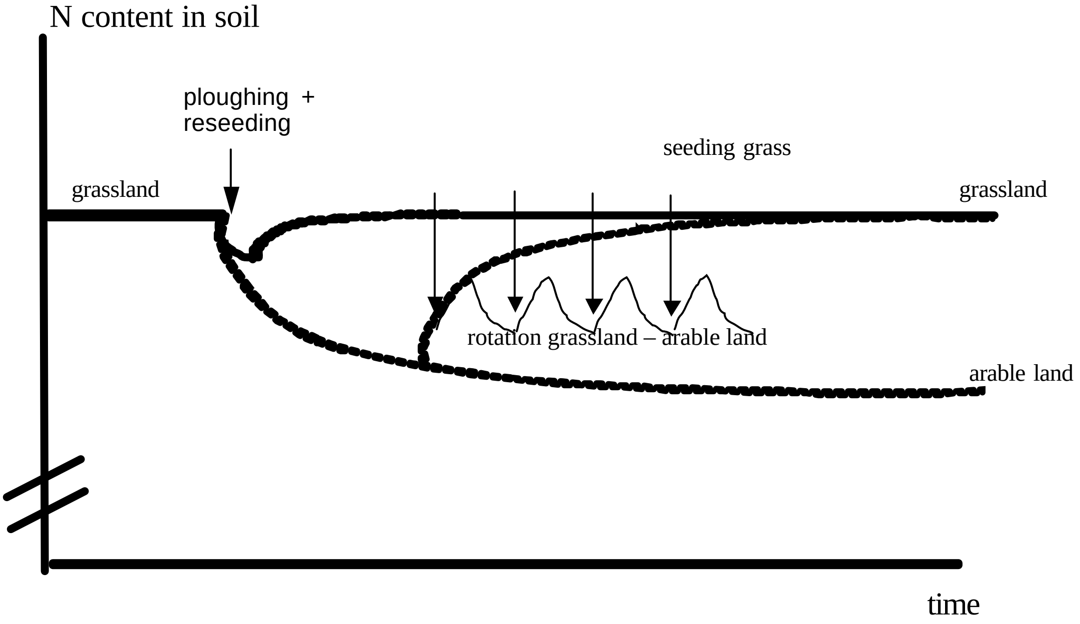

Figure 10. Schematic representation of the time course of the organic N content in grassland and the effects of ploughing and reseeding, ploughing and conversion into permanent arable land, and rotation of grassland and arable land.

6.3.2 Permanent grassland which is never ploughed

N accumulation gradually increases in permanent grassland (which is never ploughed) until an equilibrium has reached. Long-term field experiments in UK indicate that N accumulation may continue for more than 100 years (Jenkinson, 1988). The accumulation mainly occurs in the upper few centimeters, by which there is a strong gradient of total N and C and of bulk density in the soil profile of undisturbed permanent grassland. Net N mineralization rate significantly increases with ageing up to more than a factor of two in comparison to young grassland (Hoogerkamp, 1973). Studies of Cuttle & Scholefield (1995), Scholefield et al. (1993) and Van Dijk (1996) suggest that risk on N losses from grasslands increase during ageing, which may be due to a less productive sward and to less N accumulation and immobilization in the soil. The denitrification capacity may increase as well, and the ratio nitrate leaching/denitrification may decrease during ageing, but this should be further tested. In the Netherlands, most of the grasslands on mineral soils are renewed each 5-10 years, because the sward quality and yield potential decrease, e.g. because of drought, severe winter, and wet autumns. There are no studies in the Netherlands and other countries in which the yields and N losses from undisturbed old permanent grasslands are compared for a long period with permanent grasslands which are regularly ploughed. These type of studies are needed in order to conclude whether there are significant difference in N losses between permanent undisturbed grasslands and permanent grasslands that is regularly renewed.

6.3.3 Permanent grassland which is ploughed and reseeded directly

A temporary drop in total N content in the soil occurs after ploughing of grassland, followed by a N accumulation in the new sward and N immobilization in the soil (Figure 10). It is often suggested that organic N contents in these systems are in quasi-equilibrium (i.e. only relatively small fluctuations in soil N content), but there is no experimental evidence for this. It is well possible that there is a gradual decrease or increase of soil organic N, which is dependent on for example the initial N content of the soil (history), nutrient management and ploughing frequency (Figure 11). Changes in the organic N pool may affect the size of N losses. More knowledge is needed on the these changes in organic N contents. The literature study shows that ploughing grassland increases mineralization and the risk on N losses via leaching and denitrification. However, several studies indicate that the risk on leaching from ploughed grassland are much smaller when the grassland is directly reseed and especially when grassland is ploughed and reseeded in the growing season.

Adjustment of N fertilizer application, application of other essential and yield limiting nutrients, grazing and mowing frequency and intensity, water management, and pest control may all significantly affect the growth of the reseeded grass and thereby, the size of N losses. Quantitative results of effects of management on the different N processes and crop perfomance are scarce. In further research emphasis should be given to these effects, because by accurate adjustment of management to the crop and soil conditions after grassland cultivation, N use efficiency may increase and N losses may decrease.

6.3.4 Permanent grassland converted to arable land

After conversion of grassland to arable land, N mineralization is enhanced and the organic N content wil decrease in time until an equilibrium is reached for the arable soil. The time of this decrease in organic N content and the organic N at equilibrium situation strongly depends on the initial organic N content of the soil, nutrient management, soil type, weather conditions and crop type. The enhanced N mineralization increases the risk of N losses when the amount of mineralized N exceeds the N uptake of the arable crop. Leaving the soil fallow after ploughing of grassland resulted in very high leaching losses (100-300 kg N ha^{-1} yr^{-1}) (Adams & Jan, 1999; Davies et al., 2001; Lloyd, 1992). The timing of ploughing and the N uptake of following crops are important. Lloyd (1992) showed residual effects of grassland ploughing on leaching losses during the second winter, which is probably attributed to the fact that these arable soils were bare during winter. Francis (1995) showed that sowing a cover crop during winter decreased N leaching up to 60 percent. Francis (1995) indicate that a delay of ploughing grassland and conversion to arable land from autumn to spring decreased N leaching losses with 10 to 50 kg N ha^{-1} yr^{-1}**.** However, Lloyd (1992) indicated that postponing ploughing from autumn to spring may increase leaching losses in the second winter, though growing cover crops during winter may decrease N losses. Further research should focus on adjustment of N fertilization and crop type and growing cover crops in winter to decrease N losses from grassland converted into arable land.

6.3.5 Temporal grasslands in rotation with arable crops

In temporal grasslands in rotation with arable crops, a period with N accumulation during the grassland period is followed by a period of net mineralization during the arable cropping period (figure 10). The total N content is on average between that of permanent grassland and permanent arable land (figure 10). The amount of N released and the risk on N losses increases with increasing age of the sward (Figure 7; Johnston et al., 1994). The N leaching losses in different studies range from less than 60 kg N ha^{-1} after ploughing of 1 year leys to 250 kg N ha^{-1} after ploughing of 6 years leys, but factors such as management, soil type, crop, and ploughing time also differed between the studies and may strongly affect N leaching. There are several possibilities to decrease the risk on N leaching after ploughing of short-time grassland in rotation:

- Postponing cultivation of the temporal grassland from autumn to spring (e.g. Francis, 1995; Djurhuus & Olsen, 1997);
- Adjustment of N fertilizer application to the expected N mineralization from ploughed grassland (e.g. Conijn, 2000);
- Growing cover crops (e.g. Francis, 1995);
- Growing crops after ploughing of grassland with a high N uptake and a long N uptake period, such as fodder and sugar beet (e.g. Conijn, 2000).

It is not clear whether the organic N content of the soil in rotations of grassland-arable land is in equilibrium (situation B in figure 11) or gradually increases (A) or decreases (C). This change in soil organic N content may affect the N use efficiency and N losses of the system and the factors that affect these changes should be further studied.

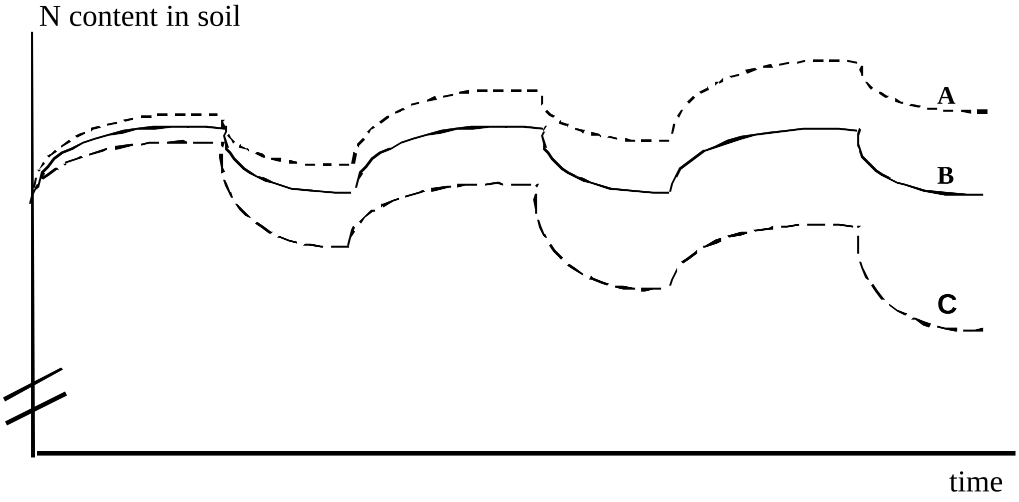

Figure 11. Schematic represenation of the time course of the N content in the soil of grassland which is regularly ploughed. System A indicates a soil with a (gradual) increase in N content, system B indicates a soil with a stable N content (i.e. fluctuating without an increasing or decreasing trend at the long-term; at equilibrium), and system C a soil with a decrease in N content. The figure is both applicable for permanent grasslands as for temporal grasslands (in rotation with arable crops), but the scales of the X-axis and Y axis differ for both systems.

6.3.6 Comparison of the cultivation systems

On basis of the previous paragraphs it is concluded that the risk of N leaching losses increases:

- with increasing grasland age;
- with increasing time between cultivation and reseeding grasland or sowing arable crop (figure 12);
- when the N uptake capacity of the preceeding crop (including a cover crop) decreases, i.e. the total N uptake and the period of N uptake (figure 12)

Thus smallest risk on N losses occurs when young grassland is cultivated and directly reseeded in spring and the largest risk when old grassland is ploughed and left fallow for a certain period (Figure 12).

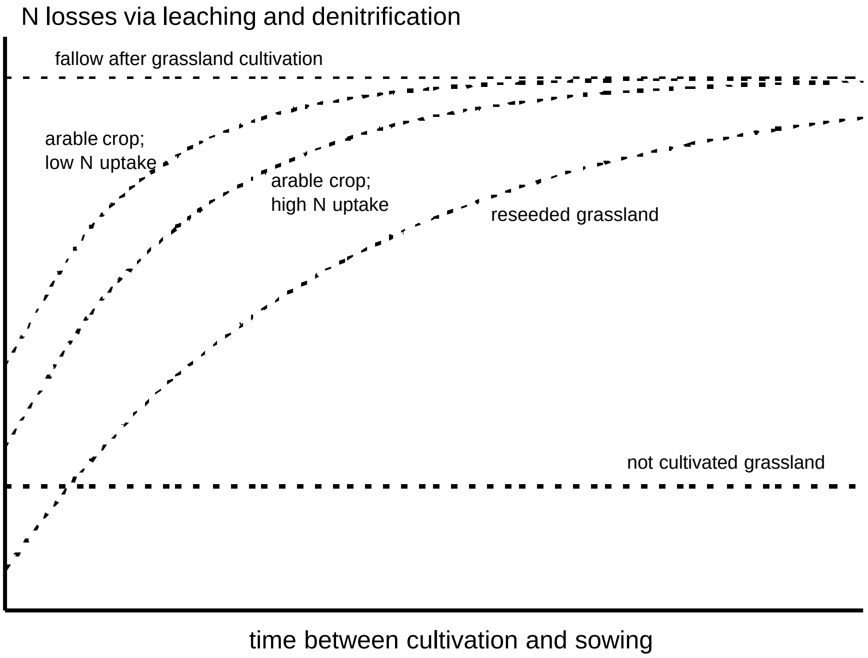

Figure 12. Schematic representation of the relationship between the time between cultivation and reseeding/sowing and the cumulative N losses, i) for reseeded grassland, ii) for grassland converted to arable land with an arable crop with a high uptake, iii) for grassland converted to arable land with an arable crop with a low N uptake iv) for not cultivated grassland, and v) for fallow after grassland cultivation. The figure indicates that N losses increase with increasing period of fallow.

6.4 Gaps in knowledge and recommendations for further studies

The major question around grassland cultivation is when and how grasslands should be cultivated in order to achieve high yields with low N losses, and especially with low nitrate leaching losses. So far, only a few studies have been carried out and, especially, a quantification of the effects of cultivation on N losses via leaching and denitrification under Dutch conditions is lacking. Therefore, it is suggested to set-up integrated experimental research in the Netherlands to increase the quantitatieve knowledge about effects of grassland cultivation on agricultural and environmental consequences. The major research topics around the effects of grassland cultivation on N processes and losses are:

- Quantitative knowledge about changes in organic N contents and net N mineralization of grassland soils with different cultivation systems during long-term experiments on different soil types;
- To test the hypothesis that cultivation and direct reseeding of grassland in spring and early summer does not increase N losses in comparison to undisturbed grassland;
- Quantification and comparison of agricultural performance and N losses from old undisturbed permanent grasslands and those from young and regularly cultivated permanent grasslands on different soil types.

- Quantitative knowledge about effects of nutrient and crop management in order to minimize risk on N losses after grassland cultivation;
- Risk assessment to determine periods of high risk on N losses after grassland cultivation, using weather, soil and crop data;
- Development and testing of soil indicators that provide information on the risk of N losses when reseeding. These type of indicators may be required when best management guidelines or integrated legislation and restrictions around grassland cultivation have to be implementend in practice.

We strongly recommend to set-up long-term integrated field experiments with a statistical design at different locations (e.g. soil type and grassland age) in which different treatments (renovation systems, grassland-arable crop rotations, N fertilizer application, time of ploughing and reseeding etc.) are compared and in which the major N processes and the performance of the crops are quantified (yield, N content, crop quality). The ultimate goals of such studies are:

- to develop and test best management guidelines for various grassland systems;
- peformance indicators for grassland management;
- accurate estimates of changes in organic N, N mineralization, N leaching losses, and denitrification as function of soil type, and grassland management and age.

Only by such integral studies it is possible to quantify the different N processes during ageing and after cultivation of grasslands and to derive management measures in order to decrease N losses to the environment. Ideally, in these studies also effects on phosphorus (P) and carbon (C) flows in the soils are quantified, because of their role in eutrophication and greenhouse gas emission, respectively.

From January 2002, a large research programme on cultivation of permanent and temporal grasslands starts (2002-2005) in the Netherlands financed by the Ministry of Agriculture, Nature Management and Fisheries. The programme addresses a large part of the mentioned suggestions for further research and includes both system analyses and field experiments. This programme aims at obtaining insight in the effects of cultivation on N and P emissions to the environment and the development of measures and tools for farmers and policy in order to achieve environmental and agricultural sound systems of permanent and temporal grasslands.

References

Adams, W.A. and M.T. Jan (1999) Utilization of nitrogen accumulated by a clover containing ley following cultivation. Soil Use and Management 15, 247-253.

Anon. 1998. Adviesbasis bemesting grasland en voedergewassen. Themaboek November 1998, Praktijkonderzoek Rundvee, Schapen en Paarden, Lelystad, 53 p.

Bhogal, A., D.V. Murphy, S. Fortune, M.A. Shepherd, D.J. Hatch, S.C. Jarvis, J.L. Gaunt and K.W.T. Goulding (2000) Distribution of nitrogen pools in the soil profile of undisturbed and reseeded grasslands. Biology and Fertility of Soils 30, 356-362.

Catalan, R.L. and B.H. Janssen (1990) Korte- en lange-termijneffecten van bemestingsmaatregelen op de stikstofmineralisatie uit organisch materiaal. Notitie ten behoeve van de Commissie Stikstof, Vakgroep Bodemkunde en Plantenvoeding, Landbouwuniversiteit Wageningen, 15 p.

Conijn, J.G. (2000) Nitraat in het grondwater in relatie tot weer en beheer. p. 35-60. In: H. Van Keulen (ed.) Duurzame melkveehouderij en stikstofmanagement. Themadag 2000: stikstofbeheer en grondwaterkwaliteit op proefboederij ‘De Marke’. Plant Research International, rapport 21, Wageningen.

Corré, W.J. (2000) De stikstofhuishouding van de bodem, p. 21-34. In: Van Keulen (ed.) Duurzame melkveehouderij en stikstofmanagement, Plant Research International, rapport 21, Wageningen.

Cuttle, S.P. and D. Scholefield (1995) Management options to limit nitrate leaching from grassland. Journal of Contaminant Hydrology 20, 299-312.

Davies, M.G., K.A. Smith and A.J.A. Vinten (2001) The mineralisation and fate of nitrogen following ploughing of grass and grass-clover swards. Biology and Fertility of Soils 33, 423-434.

Djurhuus, J. & P. Olsen (1997) Nitrate leaching after cut grass/clover leys as affected by time of ploughing. Soil Use and Management 13, 61-67.

Eriksen, J. and L.S. Jensen (2001) Soil respiration, nitrogen mineralization and uptake in barley following cultivation of grazed grasslands. Biology and Fertility of Soils 33, 139-145.

Francis, G.S. (1995) Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. Journal of Contaminant Hydrology 20, 313-327.

Gill, K, S.C. Jarvis, and D.J. Hatch (1995) Mineralization of nitrogen in long-term pasture soils: effects of management. Plant and Soil 127, 153-162.

Grootenhuis, J.A. (1961) Invloed van gescheurde kunstweiden op het produktievermogen van zavelgronden. Stikstof 3, 30, 242-252.

Hart, M.L. ’t (1950) Organische stof en grasland. Landbouwkundig tijdschrift 62, 532-542.

Hassink, J. and J.J. Neeteson (1991) Effect of grassland management on the amounts of soil organic N and C. Netherlands Journal of Agricultural Science 39, 225-236.

Hassink, J. (1994) Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. Soil Biology and Biochemistry 26, 1221-1231.

Hassink, J. (1995) Prediction of the non-fertilizer N supply of mineral grassland soils. Plant and Soil 176, 71-79.

Hoogerkamp, M. (1973a) Accumulation of organic matter under grassland and its effects on grassland and on arable crops. Agricultural Research Report 806, PUDOC, Wageningen.

Hoogerkamp, M. (1973b) De ophoping van organische stof onder grasland en de invloed hiervan op de opbrengst van grasland en akkerbouwgewassen. Instituut voor Biologisch en Scheikundig Onderzoek van Landbouwgewassen, Wageningen.

Hoogerkamp, M. (1984) Changes in productivity of grassland with ageing. Doctoral thesis, Agricultural University Wageningen, 78 p.

Huntjes, J.L.M. (1971a) Influence of living plants on immobilisation of nitrogen in permanent pastures. Plant and Soil 34, 393-404.

Huntjes, J.L.M. (1971b) The influence of living plants on mineralization and immobilization of nitrogen. Plant and Soil 35, 77-94.

Janssen, B.H., P. van der Sluijs and H.R. Ukkerman (1990) Organische stof. p.109-126. In: Locher W.P. and De Bakker H. Bodemkunde van Nederland Deel 1. Algemene Bodemkunde, Malmberg, Den Bosch.

Jarvis, S.C. and O. Oenema (2000) Measuring and monitoring nitrogen and phosphorus flows and losses in grassland systems. pp. 305-325. In: L. 't Mannetje and R.M. Jones Field and laboratory methods for grassland and animal production research. CABI Publishing, Oxon.

Jenkinson, D.S., P.B.S. Hart, J.H. Rayner, and L.C. Parry (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. Intecol Bulletin 15, 1-8.

Jenkinson, D.S. (1988) Soil organic matter and its dynamics, p. 564-607 In: Wild, A. (ed.) Russels's Soil Conditions and Plant Growth. 11th edition, Longman, New York.

Johnston, A.E., J. Mc Ewen, P.W. Lane, M.V. Hewitt, P.R. Poulton & D.P. Yeoman (1994) Effects of one to six year old ryegrass-clover leys on soil requirements of the arable sequence winter wheat, potatoes, winter wheat, winter beans (Vicia faba) grown on a snady loam soil. Journal of Agricultural Science 122, 73-89.

Kemmers, R.H. and P.C. Jansen (1985) Stikstofmineralisatie in onbemeste half-natuurlijke graslanden. ICW-rapport 14, Wageningen.

Lloyd, A. (1992) Nitrate leaching under arable land ploughed out from grass.Proceedings Fertiliser Society 330, 32 pp.

Patra, A.K., S.C. Jarvis and D.J. Hatch (1999) Nitrogen mineralization in soil layers, soil particles and macro-organic matter under grassland. Biology and Fertility of Soils 29, 38-45.

Praktijkonderzoek Veehouderij (2000) Invloed van leeftijd en N-voorgeschiedenis op de nalevering van N van gescheurde graszodes met als volg gewassen maïs en gras (in preparation).

Ryden, J.C., P.R. Ball and E.A. Garwood (1984) Nitrate leaching from grassland. Nature 311: 50-53.

Ryden, J.C. (1984) The flow of nitrogen in grassland. Proceedings No. 229. The Fertiliser Society.

Ryden, J.C. and K.P. Dawson (1982) Evaluation of the acetylene-inhibition technique for the measurement of denitrification in grassland soils.Journal of the Science of Food and Agriculture 33, 1197-1206.

Scholefield, D, K.C. Tyson, E.A. Garwood and A.C. Armstrong, J. Hawkins and A.C. Stone (1993) Nitrate leaching from grazed grassland lysimeters: effects of fertilizer input, field drainage, age of sward and patterns of weather. Journal of Soil Science 44, 601-613.

Schothorst, C.J. and D. Hettinga (1981) Het effect van diepe profielbwerking bij grasland op lichte zandgrond. Nota 1304, Instituut voor Cultuurtechniek en Waterhuishouding, Wageningen.

Shepherd, M.A.., D.A. Hatch, S.C. Jarvis & A. Bhogal (2001) Nitrate leaching from reseeded pasture Soil Use and Management 17, 97-105

Tyson, K.C., D.H. Roberts, C.R. Clement and E.A. Garwood (1990) Comparison of crop yields and soil conditions during 30 years under annual tillage or grazed pasture. Journal of Agricultural Science 115, 29-40.

Van Dijk, W., T. Baan Hofman, K. Nijssem, H. Everts, A.P. Wouters, J.G. Lamers, J. Alblas and J. van Bezooijen (1989) Effecten van maïs-gras vruchtwisseling. PAGV verslag 217, Lelystad.

Van Dijk, W., T.B. Hofman, K. Nijssen, H. Everts, A.P. Wouters, J.G. Lamers, J. Alblas, and J. van Bezooijen (1996) Effecten van mais-gras Vrucht-wisseling.Verslag Proefstation voor de Akkerbouw en de Groenteteelt in de Vollegrond No. 217, 140 pp.

Van Dijk, W. (1997) Maïs na oud grasland op klei vraagt weinig stikstof en fosfaat. Praktijkonderzoek, 10, nr. 1, 12-14.

Vellinga, Th.J., P.J. Kuikman & A. van den Pol-van Dasselaar, A. van den (2000) Beperking van lachgasemissie bij het scheuren van grasland : een systeemanalyse Alterra-rapport, 114-5, Alterra, Wageningen, 59 p

Velthof, G.L. and O. Oenema (1995) Nitrous oxide fluxes from grassland in the Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. European Journal of Soil Science 46, 541-549.

Velthof, G.L. and O. Oenema (2001) Estimation of plant-available nitrogen in soils using rapid chemical and biological methods. Submitted to Biology and Fertility of Soils.

Velthof, G.L., J.J. Neeteson, H.G. van der Meer and O. Oenema (2000) Schatting van de neto stikstofmineralisatie en biologische stikstofbinding in landbouw-gronden. Alterra, Wageningen rapport 117, 35 p.

Wisselink, G.J. (1961) Samenvattend verslag over negen jaar van een bodemvrucht-baarheidsproefbedrijf op zavelgrond in Zuid Friesland. IB-rapport 13.

Whitehead, D.C., A.W. Bristow and D.R. Lockyer (1990). Organic matter and nitrogen in the unharvested fractions of grass swards in relation to the potential for nitrate leaching after ploughing. Plant and Soil 123: 39-49.

Whitmore, A.P., Bradbury N.J. and P.A. Johnson (1992). Potential contribution of ploughed grassland to nitrate leaching. Agriculture, Ecosystems and Environment 39, 221-233.

Whitmore, A.P. (1999) Evaluating the nitrogen-supplying power of soils in field cropping systems AB-DLO, nota 186 Wageningen, 23 p.

Woldendorp, J.W. (1963) The influence of living plants on denitrification. Thesis Agricultural University, Wageningen.