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Nitrogen cycling on intensively managed boreal dairy pastures

Doctoral Dissertation

Kirsi Saarijärvi

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Academic Dissertation
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MTT Agrifood Research Finland

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Nitrogen cycling on intensively managed boreal dairy pastures

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Abstract

In Finland, pastures cover approximately 100 000 ha. Grazing is natural, cheap and the second most important feed of dairy cows in Finland. In intensive grazing 75-90 % of the N ingested by the cows is returned to the pasture in dung and urine and the nutrients are constantly recycling through soil, air, vegetation, grazing animal and excreta. Dung and urine patches are the 'hot spots' of intensive N cycling on pastures and also the main sources for the N losses that are both an economical loss for farmer and a hazard to the environment. The aim of this study was to measure the main N processes and losses of the N cycle in boreal dairy pasture systems. The experiments were mostly conducted on 'lysimeter field' at MTT Agrifood Research, Maaninka. Pasture N utilization is ineffective compared to silage cutting especially when high amounts of concentrates or protein supplementation is used. Transformations and immobilisation/mineralization turnover of N are high due to short term ley conditions. When the management changes almost yearly, the soil N is in constant state of change and equilibrium is never achieved. Nitrogen is accumulated in soil during grass cover years and mineralized during the renewal year. Thus, N fertilization for newly sown sward and cover crop after pasture renewal is not needed. In winter microbial activity in soil slows down, but still continues even in temperatures below zero. Freezing prevents most water movement in soil and nitrate therefore accumulates. Nitrogen discharges in spring through leaching and gaseous losses when soil thaws and snow cover melts. Leaching of N is largest after pasture renewal. Nitrogen loss in surface runoff is small and not important during the whole ley period. A white clover mixture decreases N leaching losses at pasture and offers more efficient N utilization compared to a 220 kg N ha^{-1} y^{-1} fertilized grass sward. The importance of pastures as a source of NH_3 emission in Finland is minor and has been overestimated previously. Nitrous oxide emissions from pastures were also smaller than estimated in the IPCC report. The watering facility area functions as a cattle congregation area. Thus it receives a large amount of excretal N and suffers treading damage that destroys the vegetation and soil pore structure causing N leaching losses, surface runoff and gaseous emissions. Based on these results, it is essential to include the whole ley rotation in short-term ley studies because of the cumulative effect of N inputs in previous years and the N mineralization pulse after cultivation of the soil, which greatly increases N losses.

Key words: pasture, leaching, gaseous emissions, mineralization, nitrogen use efficiency, modelling

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Intensiivisen lypsykarjalaitumen typpikierto

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Tiivistelmä

Maamme viljellystä peltoalasta noin 100 000 ha on laitumia. Laidun on märehtijöiden luonnollista ravintoa, tuottajan kannalta halvinta rehua ja toiseksi tärkein karkearehu lypsylehmien ruokinnassa. Noin 75 – 90 % lehmän syömästä typestä palaa ulosteiden mukana takaisin laitumelle ja ravinteet kiertävät maan, ilman, kasvuston, eläimen ja ulosteiden kehässä. Sontakasojen ja virtsalaikkujen paikallinen typpikuormitus on suuri, joten sekä huuhtoutumista että kaasumaisia päästöjä tiedetään syntyvän. Typpihävikki on paitsi haitta ympäristölle, myös taloudellinen tappio viljelijälle. Tämän tutkimuksen tavoite oli selvittää laitumen typpikierron volyymit sekä tärkeimmät hävikkikohdat pohjoisissa olosuhteissa. Tutkimukset tehtiin pääosin MTT:n Maaningan toimipisteen lysimetrikentällä. Laitumen typen hyväksikäyttö on heikko verrattuna niittonurmien typen hyväksikäyttöön. Hyväksikäyttöä heikentää entisestään runsas valkuaispitoisen väkirehun käyttö. Nurmikierrossa typen immobilisaatio/mineralisaatio -suhde muuttuu jatkuvasti uusimisen ja nurmivuosien aikana, siksi pitkäaikaisille nurmille tyypillistä tasapainotilaa, jossa input ja output ovat yhtä suuria, ei koskaan saavuteta. Typpeä kumuloituu kyntökerrokseen nurmivuosien aikana ja sitä vapautuu nurmen uusimisen jälkeen, joten uusimisen jälkeen kylvetty uusi kasvusto ei tarvitse lisätyppilannoitusta. Talven aikana maan mikrobitoiminta hidastuu, mutta ei pysähdy kokonaan. Sen sijaan veden liikkeet ovat jäisessä maassa vähäisiä ja nitraattityppeä kumuloituu pintamaahan. Suurin huuhtoutumispulssi tuleekin keväällä, kun runsaasti vettä sisältävä lumi sulaa. Huuhtoutuminen on erityisen runsasta uusimisen jälkeen. Sen sijaan pintavalunnan merkitys typen osalta on vähäinen. Talvenkestävän valkoapilalajikkeen käyttö laitumessa typpilannoituksen sijaan vähensi typen huuhtoutumista. Valkoapilalaitumen tuottavuus oli lähes yhtä hyvä kuin lannoitetun heinälaitumen. Eritteistä haihtuneet ammoniakin määrä oli pienempi kuin aiemmissa arvioissa on esitetty. Laitumen merkitys ammoniakkipäästöjen lähteenä Suomessa on olematon. Myös typpioksiduulin päästömäärä on aiemmin yliarvioitu. Lehmien juomapaikalle kertyy paljon ulosteita ja tallaus hävittää kasvuston ja rikkoo pintamaan huokosrakenteen, mikä johtaa sekä huuhtoutumisen että kaasumaisten päästöjen lisääntymiseen. Tulosten perusteella nurmien ympäristövaikutuksia tutkittaessa on erittäin tärkeää ottaa mukaan koko nurmikierto, koska päästöjen osuudet vaihtelevat huomattavasti kierron eri ajankohtina.

Avainsanat: laidun, huuhtoutuminen, kaasumaiset päästöt, mineralisaatio, typen hyväkaikäyttö, mallintaminen

Foreword

The research projects presented here were conducted at MTT Agrifood Research Finland during 1998-2005. The field experiments were carried out in the MTT research station at Maaninka. Work was financially supported by Ministry of Agriculture and Forestry and the Finnish Cultural Foundation National funds and North Savo, Alma and Jussi Jalkanen funds.

I am grateful to Marjatta Suvitie, MTT, for providing me the facilities and support for carrying out the experiments at Maaninka research station. Gratitude is also expressed to Professor Pertti Pasanen, Department of Environmental Science.

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The Greatest thanks of all I owe to my husband Erkki for bearing me through these years. He has proven me that it is true: for better or for worse, in sickness and in health…

Alapitkä November 2008

Kirsi Saarijärvi

List of original articles

The thesis is a summary and discussion of the following articles, which are referred to by their Roman numerals:

I Saarijärvi, K and Virkajärvi, P (2008) N dynamics in dung and urine patches on intensively managed pasture on sandy soil in Finland. Manuscript submitted to Journal of Agricultural Science, Cambridge (28.8.2008)

II Saarijärvi, K, Virkajärvi, P, Heinonen-Tanski, H and Taipalinen, I. (2004) N and P leaching and microbial contamination from intensively managed pasture and cut sward on sandy soil in Finland. Agriculture, Ecosystems and Environment 104, 3: 621-630.

III Saarijärvi, K, Virkajärvi, P, Heinonen-Tanski, H (2007) Nitrogen leaching and herbage production on intensively managed grass and grass-clover pastures on sandy soil in Finland. European Journal of Soil Science 58: 1382-1392.

IV Saarijärvi, K, Mattila, P and Virkajärvi, P. (2006) Ammonia volatilization from artificial dung and urine patches measured by the equilibrium concentration technique (JTI method). Atmospheric Environment 40 27:5137-5145.

The authors contribution in joint publications

I Kirsi Saarijärvi planned and conducted the experiment, calculated and interpreted the results, and was mainly responsible for writing the paper.

II Kirsi Saarijärvi conducted the most of the experiment, calculated and interpreted the results, and was mainly responsible for writing the paper.

III Kirsi Saarijärvi planned and conducted the experiment, calculated and interpreted the results, was mainly responsible for writing the paper.

IV Kirsi Saarijärvi planned and conducted the experiment, calculated and interpreted the results, and was mainly responsible for writing the paper.

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Abbreviations

DM	Dry matter
DON	Dissolved organic N
DWS	Drinking water supply
ECM	Energy corrected milk yield
GD	Grazing day
HA	Herbage allowance
HI	Herbage intake
HM	Herbage mass kg DM ha^{-1}
LU	Livestock unit
LUGD	Livestock units per grazing days
N	Nitrogen
NH_3-N	Ammonia-N
NH_4-N	Ammonium-N
NO_3-N	Nitrate-N
N_2O	Nitrous oxide
NO	Nitrogen oxide
OM	Organic matter
RHM	Rejected herbage mass
SON	Soluble organic N
SMN	Soil mineral N
SNF	Symbiotic N fixation
SOM	Soil organic matter
SR	Stocking rate LU ha^{-1}
TSN	Total soluble N

Contents

1 Introduction

1.1 Why make yet another study about N cycling on pastures?

It is well known that nitrogen (N) cycling on intensive dairy pasture is quite vigorous as only 25-30 % of the N ingested by cows is retained in milk or foetal growth (Haynes and Williams 1993). Rest of the N is excreted either back to the pasture or to the milking parlour in dung and urine. Excess N incurs eutrophication and acidification in the environment. Thus, the studies concerning N cycling on pastures and N emissions from pasture are numerous (Scholefield et al. 1991; Haynes and Williams 1993; Jarvis 1993; Ledgard et al. 1999; Stenberg et al. 1999; Eriksen and Jensen 2001; Eriksen et al. 2004; Wachendorf et al. 2004; Monaghan et al. 2005; Seidel et al. 2007; Humphreys 2008). The main reason for this thesis was that scientific data from the Nordic area, was limited.

There are several differences between Nordic and temperate regions that influence the N cycle. In Central Finland, the main dairy production area of the country, the growing season is quite short but extremely intense because of the day length. The soil freezes to > 20 cm depth and the snow cover period lasts over 5 months per year. Mean annual temperature (1971-2000) in the region is 2.8°C and annual precipitation is between 400-700 mm, of which approximately 30 – 50 % falls as snow. Occasionally, the temperature can drop below -30°C. During the frost period most water movement in soil is prevented. In spring, the snow cover melts and there is a large leaching and surface runoff pulse that usually fades away as fast as it starts. At the same time there is also an N_2O pulse from the melting soil (Christensen and Tiedje 1990). The soils are usually somewhat acidic ($pH < 6$), which should reduce ammonia volatilization (O`Toole et al. 1985), but there are no results from dung and urine excreted on pasture in Nordic areas.

Even though the bedrock underneath Finland is one of the oldest in the world, soils above it are quite young due to the massive effect of the latest glaciation (Donner 1995). This affects for example NH_4 and NH_3 dynamics, as ammonium ions can be attached to weathering clay minerals in soil. Soil cation exchange capacity and thus NH_4 dynamics depend on the structure and weathering state of different clay minerals (Liang and MacKenzie 1994). The clay minerals in Finnish soils are younger and less weathered and thus can bind less ammonium ions than older clays in for example Central Europe and the British Isles. The climate in Finland is comparable to large parts of Scandinavia, Russia, Canada and northern parts of USA and the results of this study should be generally applicable to intensive dairy pastures in these areas.

The most important grass species used for silage and pasture in Finland are timothy (*Phleum pratense* L.) and meadow fescue (*Festuca pratensis* Huds.), as perennial ryegrass does not survive well in Nordic conditions. The grass species used differ from ryegrass in their growth patterns, sward structure and competitivity, and this makes the composition of the swards different from that of ryegrass swards (Gooding and Frame, 1997). When the cost of energy and commercial fertilizers is rising, legumes become more interesting as a N source for swards. Use of white clover (*Trifolium repens* L.) in pasture mixes is common in temperate grazing areas in the British Isles and New Zealand, but recently the interest to use new winter hardy cultivars of white clover has risen in Finland (Kuusela 2004a).

There are four to five grazing rotations per summer, depending on the weather conditions, and the recommended fertilizer level is 190 kg N ha^{-1}, divided into three applications per grazing season (Virkajärvi 2005). This is high related to a short grazing season and fertilizer recommendations for silage (200 kg N ha^{-1} year^{-1}; 2 cuts). Furthermore, rapid melting of snow and soil thawing may have a considerable effect on N transformations in soil and N emissions from soils (Maljanen et al. 2007).

Dairy production in Finland is intense. The average milk production of cows is up to 8000 kg y^{-1} and the level of supplementation and the diet N content are high (Virtanen and Nousiainen 2005). Thus there is high N input to the pasture system in the form of urea in addition to fertilizer N. Due to the facts mentioned above, there was a clear need to produce new data for Nordic conditions to be able to reduce and counteract the harmful environmental and economical effects of N losses from intensive pasture systems.

1.2 Soil-Plant-Animal relationships at pasture

Grazing cows have various impacts on pasture nitrogen dynamics (Fig 1). Most important effects on pasture soil and vegetation are caused by excretal nutrient returns to the pasture. Other meaningful effects are the spatial removal of vegetation by grazing and treading damage to the plants and soil. Environmental impacts of these factors depend on the intensity of grazing. A difficulty in pasture studies is the uneven use of the pasture area by cattle. The pattern of excretal returns and treading damage is greatly influenced by pasture management (e.g. stocking rate, continuous grazing, strip grazing) and stock behaviour (e.g. camping areas, animal traffic routes) (Haynes and Williams 1993).

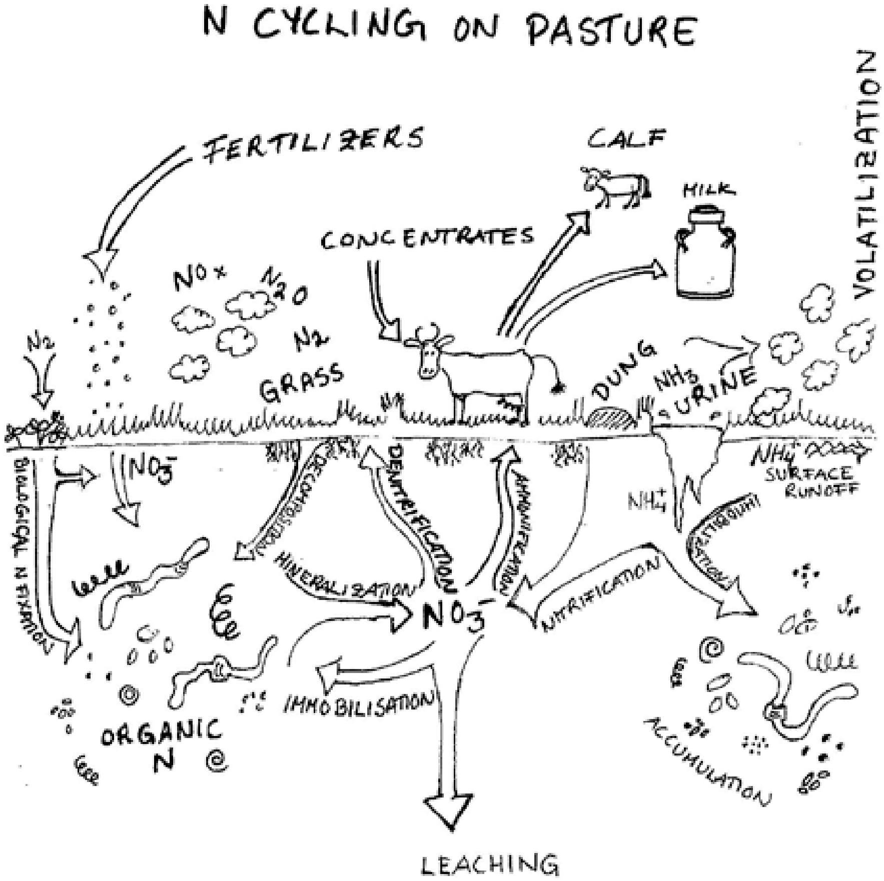

Figure 1. Pasture nitrogen cycle is complex as N can be in many different physical and chemical forms.

1.2.1 Dung and urine as N sources

Dung and urine patches are the ’hot spots’ of intensive N cycling in pastures and also the main sources for N loss. As N is excreted both in organic and mineral form and furthermore in many different physical forms which have different solubility, it is a difficult nutrient to follow and control. The N transformation reactions in soils include mineralization, immobilization, nitrification, denitrification, NH_3 volatilization, NH_4^+ fixation and NO_3^- leaching (Bolan et al. 2004).

The concentration of total N in dung is 3.4-5.0 g/kg and in urine 4.8-13.3 g/kg depending on the N content of the diet (Petersen et al. 1998). Typically, over 70% (range 50 to 90 %) of the N in fresh urine is present as urea and the rest consists of amino acids and peptides (Haynes and Williams 1993). About 20-25 % of faecal N is water soluble, 15-25 % is undigested dietary N and the remaining 50-65 % is present in bacterial cells (Oenema et al. 1997). As the surface area covered by single defecation and urination are small, the local N load often exceeds 1000 kg N ha^{-1} in dung pats and 500 kg N ha^{-1} in urine patches (Whitehead 1995). Excretal patches have both physical and chemical impacts on pasture vegetation and soil.

Large amount of nutrients deposited on a single patch give an unlimited nutrient supply for plant growth. However, in urine patches the dose is so large, that it may cause damage to the leaves and roots and decrease the ability of grass to fully utilize the N available (Shand et al. 2002). Despite the damaging effect, the DM and N yield in urine patches deposited during the growing season are usually higher than in other parts of the pasture (Fraser et al. 1994; Clough et al. 1998; Decau et al. 2003).

Most of the dung N is in organic form and releases slowly to the soil (Wachendorf et al. 2005) so N concentration of dung does not damage the sward. On the other hand, a dung pat has a suffocating effect on vegetation as it covers the soil surface completely and prevents the access of light to the soil underneath it (Weeda, 1967). Even though the patch has a negative effect on grass growth at the patch location, the influence on surrounding grass growth is strongly positive due to the light and nutrient supply and DM yield of the whole dung pat affected area can be high (Weeda, 1967; Deenen and Middelkoop 1992). Depending on the stocking rate, management intensity and duration of the growing season urine, and dung may cover 20-50 % of the pasture surface area (Afzal and Adams, 1992; Vinther, 1998).

In perennial ryegrass swards both the number of tillers and the grass N concentration increase when there is extra light and N available, and this leads to higher DM production and higher N yield of the sward (Williams and Haynes 1994; Phillips et al. 1999). However, the main grasses in our swards, meadow fescue and timothy, are weaker competitors than ryegrass in urine patches with high N concentrations (Gooding and Frame 1997; Vinther 1998).

The proportion of white clover in mixed ryegrass–white clover swards is known to decrease, especially in urine patches, as ryegrass makes more effective use of soil mineral N. The effect is caused by an increase in the number of ryegrass tillers, not directly by decreasing the number of clover stolons (Vinther 1998; Menneer et al. 2003). In Nordic conditions, proportion of white clover usually decreases during the grazing years since clover suffers from severe winter conditions more than the temperate grass species timothy and meadow fescue (Kuusela 2004b).

The excretal N not taken up by plants ends up either immobilized in the soil organic matter or is lost by leaching or gaseous forms. Immobilization from urine ranges from 13 to 25 % (Whitehead et al. 1990; Decau et al. 2003; Wachendorf et al. 2008). It is not surprising, that a large proportion of slowly degrading dung N is immobilized or not mineralized at all. Up to 70 % of dung organic matter can be carried to soil by earthworms and dung beetle larvae (Holter 1979).

The total amount of N leached under urine patches (18-58 %) depends on the soil texture (Clough et al. 1998, Decau et al. 2003), application time (Ledgard et al. 1988; Cuttle and Bourne 1993; Di and Cameron 2002; Decau et al. 2003; Stout 2003), the amount of urine (Thompson and Fillery 1997; Stout 2003), and the botanical composition of the pasture (Loiseau et al. 2001). Nitrogen leaching from dung pats during the first year after deposition is small (2-11 %) as the bulk of the N in fresh faeces is in slowly degrading organic form (Stout et al. 1997; Wachendorf et al. 2005).

Losses of NH_3 from urine patches generally represent 4-46 % of urine N (Bolan et al. 2004). Losses of NH_3 from dung are much smaller varying between 1-13 % of dung N (Whitehead 1995). Losses through denitrification in favourable conditions may account for up to 40 % of urine N (Bolan et al. 2004), but the denitrification rate and the ratio between N_2, N_2O and NO are highly dependent on soil and climatic conditions, for example, soil water status, oxygen supply, texture, available N and C and temperature (Luo et al. 1999). Furthermore, the results from experiments that include all these products of the denitrification process are scarce (Dittert et al. 2005).

1.2.2 Physical effects of grazing on vegetation and soil

Grazing usually removes less than 50 % of the total above ground herbage mass available during one year and the rest is decomposed into soil organic matter (Parsons et al. 1983). Especially in rejected areas that cover 0-60 % of the pasture area depending on the herbage allowance (Johansen and Hoglind 2007), decomposing herbage matter adds marked amounts of C and N to the surface soil. Negative effects of grazing on herbage N utilization compared to cutting treatments are widely reported in the literature (Deenen 1994; Vellinga and Andre, 1999).

Treading causes soil compaction, especially on cattle congregation areas. Treading damage to soil and vegetation can range from nil to poaching to severely puddled soil, depending on stocking rate and soil water content (Greenwood and McKenzie 2001). In wet soil conditions, compaction enhances denitrification and N_2O emissions (Menneer et al. 2005). Treading also affects the soil's continuous macropore structure especially from surface layers, which prevents the water from infiltrating into the soil and thus causes more surface runoff (McDowell et al. 2003; Pietola et al. 2005). This may actually be beneficial preventing N leaching (Cuttle et al. 2004), but the negative side is that it causes more gaseous nitrogen emissions and N and phosphorus losses in surface runoff. Treading may also decrease the sward growth and weaken the N utilization ability of vegetation (Kelly 1985; Unger and Kaspar 1994). However, there are conflicting reports on this matter (Carter 1977).

1.3 Purpose of this study

The main goal of this study was to form a holistic view of N cycling and the main N loss processes in pastures in Nordic conditions by an empirical research approach. The N transformations in soils include mineralization, immobilization, nitrification, denitrification, NH_3 volatilization, NH_4^+ fixation and NO_3^- leaching (Bolan et al. 2004) and all these processes were at least partially included in the experiments of this study to be combined in an overall systems approach. To achieve the main goal, four separate experiments were established:

In EXP I the aims were to investigate the fertilizer, urine and dung N transformations in pasture soil and to measure the N utilization of the timothy-meadow fescue sward in time and space.

In EXP II the aim was to study if N leaching from fertilized cut and grazed areas represents a threat to groundwater in areas of deep soil frost and snow cover during the production years and the renewal year. Attention was also paid to the watering point on pasture.

In EXP III the aims were to compare the N leaching from fertilized grass and unfertilized grass-clover pastures during the production years and the renewal year. Attention was also paid to the surface runoff from fertilized grass pasture. In addition, herbage and milk production of fertilized grass and unfertilized grass-clover pastures were compared.

The aim of EXP IV was to investigate the dynamics of NH_3 volatilization on intensively managed pasture. The other aim was to clarify the effect of rainfall on NH_3 volatilization on a soil type typical to the dairy production area in Finland.

2 Materials and methods

2.1 The experimental site

All the experiments were carried out at Agrifood Research Finland (MTT), Maaninka (63°10'N, 27°18'E; Fig 2). The soil type according to FAO classification is Dystric Regosol, medium textured. Soil particle size distribution of the main study area (lysimeter field) is presented in Table 1. Organic matter content of the soil is 5.65 %. The dry bulk density (BD) of the soil to 10 cm depth is 1.32 g cm^{-3} and particle density (PD) is 2.57 g cm^{-3}. The average depth of the groundwater was 5.2 – 5.8 m from the soil surface.

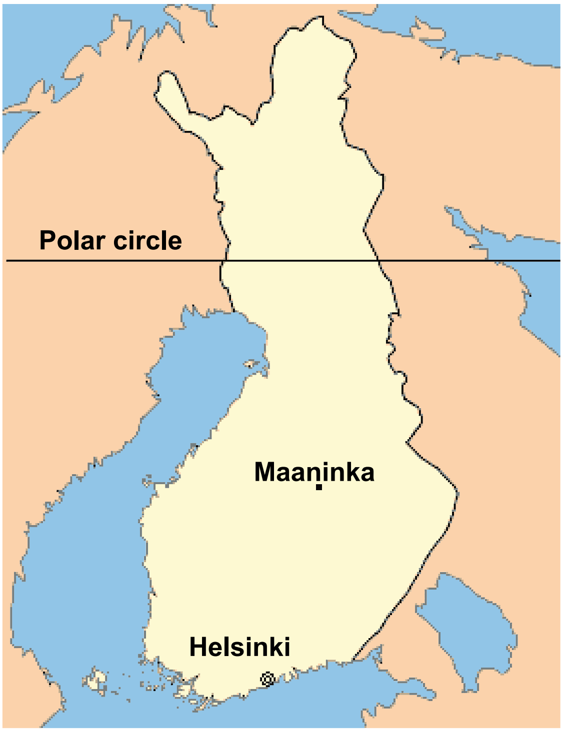

Figure 2. The location of the experimental site in Finland.

Table 1 Soil particle size distribution (%) of the lysimeter field at a depth of 0-25 cm and 25-60 cm.

Depth cm	<0.002 mm	0.002-0.006 mm	0.006-0.02 mm	0.02-0.06 mm	0.06-0.2 mm	0.2-0.6 mm	0.6-2 mm
0-25	6.9	5.3	11.7	22.5	42.6	10.0	1.1
25-60	7.0	6.4	12.3	20.5	43.7	9.5	0.6

The experimental field where EXP II and III took place consisted of 12 repacked plastic sheet lysimeters established in winter 1985-1986. The lysimeter field had a slope of 0.6 % towards the water sample collection point (Fig. 3). The upper edge of the 10 x 10 m lysimeters was 30 cm under the soil surface, and the depth of the lysimeters was 1.8 m. Each lysimeter drained through a pipe located 110 cm below the ground surface (Fig. 4).

In the EXP II the amount of leachate was recorded and composite samples of the leachate were collected monthly, except during dry periods when no leaching occurred.

In the EXP III the amount of leachate was recorded and composite samples were collected every 15-20 mm. The amount of surface runoff was recorded from water collected from two 400 m^2 plots every 10-15 mm. A hydrological year (1 June – 31 May) was used instead of the calendar year, since leaching in spring is mostly affected by the treatments and procedures accomplished during the previous summer and autumn. Soil samples were taken from each lysimeter prior to the experiment and each year in autumn before soil frost.

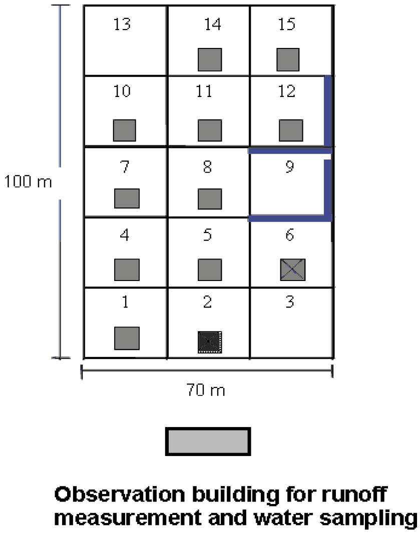

Figure 3. The map of the lysimeter field. Grey squares in numbered plots represent the 12 lysimeters and the ones without the squares represent the drainage plots. Water analyses of lysimeter and drainage plots 2, 3, 6, 9 and 13 were not included in these experiments, but the water amounts were recorded. Thicker lines on the right side of the field represent the surface runoff collectors on two lysimeter plots.

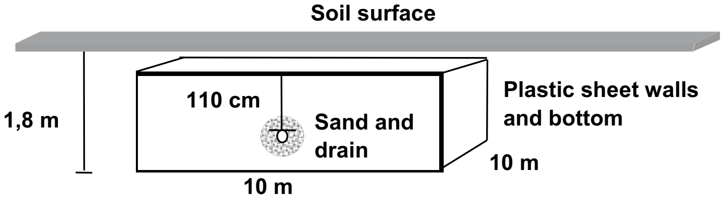

Figure 4. The structure of a single lysimeter.

2.2 Climatic conditions and weather

Precipitation, temperature, effective temperature sum, pan evaporation (Class A), frost depth and snow cover were measured at a meteorological station located 200 meters from the lysimeter field. The field was irrigated three times with 40 mm of water during the dry summer of 1999, once in July and twice in September. The potential soil water deficit (SWD) was calculated using the following formula: potential SWD = sum of rainfall and irrigation (mm) May-September – sum of pan evaporation (mm) May-September.

2.3 Dung and urine used in experiments

The average volume and size of the single urination and defecation used in EXP I and IV were measured from high producing Holstein-Friesian milking cows. The average weight of a single defecation was 2.47 kg (SE 0.29) and urination 2.37 kg (SE 0.30). The average surface area of a dung pat was determined by measuring the cross diameters of 15 dung pats on the pasture. The surface area of average size urination was determined by placing a paper on the urine spot (6 replicates) and pressing it to the ground with a plate. The size of the wet area on the paper was measured.

The excreta used in the experiment were collected from grazing cows during milking one hour before applying the excreta to the field; dung and urine were collected in separate containers, mixed, sampled and then applied to the field.

Nitrogen excretion during milking was estimated based on the difference between N intake and N output in milk. All the figures were calculated per hectare. Dry matter intake was assumed to be the same as the intake measured from a physiological experiment conducted with cows from the same herd offered fresh cut grass ad libitum and similar concentrate supplementation as in this experiment (Sairanen et al. 2005). The N in concentrates was also included in total N intake. The N excreted in milk was reduced from total N intake and the difference was assumed to be excreted in faeces. The difference was divided by 24 to get an estimate of N excretion in dung and urine per hour. As the cows spent 6 hours in the milking parlour each day, the estimated N excretion per hour was multiplied by 6 to get the total amount of N excreted during milking.

The urine N amount in this study was calculated from the total N intake partition between milk, dung and urine based on the results from a physiological experiment (Sairanen et al. 2005) conducted with the same herd and concentrate supply as that used in this experiment.

Table 2. Precipitation, snow cover, maximum water in snow, frost dates, lysimeter runoff and surface runoff of experimental years represented for hydrological years (1.6.-31.5.).

Hydrological year	Precipitation mm	Snow cover dates	Max water in snow mm	Frost dates	Max frost depth cm	Lysimeters mm	Surface runoff mm
1998-1999	657	5.12.-17.4.	nd	6.11.-5.5.	28	116	nd
1999-2000	525(1	1.12.-24.4.	nd	14.11.-26.4.	10	310	nd
2000-2001	696	20.12.-23.4.	nd	18.12.-26.4.	28	306	135(2
2001-2002	498	14.11.-25.4.	nd	5.11.-1.5.	10	109	106
2002-2003	521	6.11.-20.4.	144	18.10.-7.5.	31	130	66
2003-2004	625	21.11.-27.4.	138	9.12.-5.5.	26	196	98
2004-2005	672	15.11.-24.4.	145	15.11.-22.4.	24	397	107

1) In addition to precipitation, the lysimeter field received 40 mm of irrigation water in summer 1999 (not included in 525 mm).

2) 1.11.2000-31.5.2001

2.4 Measured parameters

Table 3. Methods used in the soil, water, crop, dung and urine, milk and weather analyses and measurements of the experiments.

Property	Method	Paper
Soil		
Dry matter content	Oven drying (105ºC)	I, III, IV
Particle size distribution	Dry sieving	I, II, III, IV
Organic matter concentration	Combustion in 500ºC	I, II, III, IV
Moisture content	Theta Probe, type ML2	I, III, IV
	Tensiometer, depths 20 cm and 40 cm	I, II, III, IV
Cation exchange capacity	ammonium acetate extraction PH7	IV
Soil temperature	Hobo H8 Onset Computer Corporation	I, IV
Total N	Leco FP 428	III
Total soluble N	Shaking the soil for 2 hours with 2 M KCl at ratio 1:5 soil and water respectively, analysed by autoanalyser	I
NO_3 and NH_4		I
Soluble Organic N	Total soluble N - (NO_3N + NH_4N)	I
Organic C	Leco FP 428	II, III
Soil compaction	Penetrometer (Findlay, Irvine Ltd, Penquick, UK)	III

Table 3. Continues.

Property	Method	Paper
Water		
Total N	Colorimetrically by autoanalyser. Methods: SFS 3031, SF-EN ISO 13395	II, III
NO_3^-	Colorimetrically by autoanalyser. Methods: SFS 3031, SF-EN ISO 13395	II
NH_4^+	Colorimetrically by autoanalyser. Method: SFS 3032	II
NO_3^- and NH_4^+	Colorimetrically by autoanalyser (Quickchem AE, Lachat)	III
Soluble organic N	Total soluble N - (NO_3N + NH_4N)	III
Leachate mm	Collected from ten 100 m^2 lysimeters in field	I, II, III
Surface runoff mm	Collected from two 400 m^2 plots in field	I, III
Microbes	Several methods, see paper II	II
Crop		
Dry matter content	Oven drying (105ºC)	I, II, III
Herbage dry matter yield	Cutting series of subsamples from treatment area before grazing or cutting	I, II, III
Botanical composition of the sward	Separation by hand	II, III
Organic matter digestability	Cellulase method (a modification of Friedel and Poppe, 1990)	III
Total N in dry matter	Leco FP 428	III
Dung and urine		
Dry matter content	Oven drying (105ºC)	I, II, III, IV
Total N	Kjeldahl method	IV
	Leco FTP 428	I, IV
NO_3^- and NH_4^+	distilled/colorimetrically by autoanalyser (Quickchem AE, Lachat)	I, IV
Organic C	Leco FTP 428	I
Volatilization of NH_3	Equilibrium concentration technique (JTI method)	IV
Milk		
Milk amount	Measured from individual cows at each milking	II, III
N	Milcoscan 605	II, III
Energy corrected milk	Milk kg*(383*fat-%+242*protein-%+783.2)/3140	II, III
Weather		
Temperature	Weather station	II, III
Temperature	Hobo H8 Onset Computer Corporation	I, IV
Precipitation	Weather station, Class A	I, II, III, IV
Pan evaporation	Weather station	I, II, III, IV
Relative humidity	Thermohygrograph	IV
Wind speed	Cup anemometer	IV
Frost depth	Weather station, tubes	I, II, III
Snow cover depth	Weather station	I, II, III

2.5 Experiments

In EXP I the effect of excreta on soil and herbage production was studied in a one year experiment between 9 June 2003 and 5 May 2004. The experimental design was randomised complete blocks (three replicate blocks) with three treatments: control, average-size urine patches and dung pats. The soil sampling in the urine and control patch was done 0, 1, 3, 5, 10, 21, 49, 77, 127 and 332 days after the start of the experiment. Sampling depths were 0-2, 2-10, 10-25, 25-45 and 45-60 cm. Grass was cut to 7 cm stubble height and herbage mass (HM) was measured from all treatments.

In EXP II six lysimeters were harvested by cutting and five lysimeters by grazing (Table 4). A watering point was placed on one of the grazed lysimeters. During the first two years of the study the pasture lysimeters were rotationally grazed by dairy cows five times per growing season and the other part was cut for silage three times per season (for detailed description see paper II).

In EXP III ten lysimeters were used in the experiment with five being assigned to the grass and five to the grass-clover treatment as a randomised complete block design (Table 4). The area was ploughed in May 2004 and sown without fertilizer in the same month with a barley cover crop and Italian ryegrass. The area was cut for silage and grazed once in the autumn (11-16 September).

In addition to measurements in EXP III described in paper III, soil penetrometer resistance was determined at 0.02 m increments to a depth of 0.35 m with a penetrometer equipped with a 12.8 mm diameter (30” angle) cone mounted on a relieved shaft and driven at approximately 0.03 m s^{-1} (Findlay, Irvine Ltd, Penquick, UK). Results are given as the average of 20 replicates at each depth in a plot. The soil of the experimental field was near to field capacity when the resistance was measured.

In EXP IV the aim was to measure ammonia volatilization from urine and dung. The experiment consisted of two part-experiments that took place 2002 and 2003. In Part-Exp 1 there were four replicates for both urine and dung and one background patch. In Part-Exp 2 the treatments were 1) no irrigation 2) 5 + 5 mm irrigation and 3) 20 mm irrigation on urine patch. There were three replicates of the irrigation treatments and a background patch. In both experiments the total amount of NH_3-N emitted was calculated based on surface coverage of dung and urine (4 % and 17 % of the pasture per year, respectively) at the average intensive grazing pressure. NH_3 volatilization was measured with the equilibrium concentration technique (JTI method, Svensson 1994).

Table 4. Experimental treatments on each lysimeter field in Exp II and Exp III.

		1	4	5	7	8	10	11	12	14	15
Exp II	1998-1999	Cut	Graz	Cut	Cut	Cut	Graz	WpG	Cut	Graz	Cut
Exp II	2000	R	R	R	R	R	R	R	R	R	R
Exp III	2001-2003	Grass	Clo	Grass	Clo	Clo	Grass	WpC	Grass	WpG	Clo
Exp III	2004	R	R	R	R	R	R	R	R	R	R

In Exp II: Cut = cut for silage, Graz = grazed, WpG = Watering point grazed, R = renewal of the sward

In Exp III: Grass = grazed grass, Clo = grazed grass-clover, WpG = Watering point grass WpC = Watering point clover, R = renewal of the sward

2.6 Statistical analysis of the experiments

The effect of treatments on measured variables were generally analysed using analysis of variance (ANOVA) according to individual experimental design. The experiments were analysed as randomized complete blocks (I and III) or completely randomized (II, IV) designs with SAS MIXED procedure (SAS Institute 1991, Littell et al. 1996). For time series repeated measurements structure was used when appropriate (e.g. lysimeter data in EXP II and III), but not if the samplings were destructive as was the case with artificial dung and urine pats in EXP I. In each analysis, the corresponding covariance structure was chosen using both Schwarz's Bayesian criterion and Akaike's information criterion. Annual means and sums were generally calculated by calendar year but in leachate data hydrological year (from 1st June to 31st May) was used instead in EXP III. In data analysis of leaching experiments the data from watering points were excluded and analysed separately.

Comparisons of treatment means were performed using Tukey's procedure or contrast statements. Validity of assumptions of data and residual diagnostics were checked graphically using SAS UNIVARIATE procedure. When the data were not directly adequate for the analysis of variance, as the variances of the treatments were unequal, log (10) or square root transformations were used. The original mean values are presented because of their usefulness in estimating biological responses.

3 Results and discussion

3.1 Grazing management

In experiments concerning environmental impacts of grassland farming there should be a connection between herbage or animal production and nutrient leaching. In order to make consistent and reliable comparisons across different production environments, an adequate description of the production system, e.g. stocking rate or herbage allowance, is needed.

In these experiments the number of grazing cows depended on the previous studies of pasture utilization with average amount of concentrates (Virkajärvi 2004). The gross herbage production was measured at the beginning of each grazing event. Dry matter intake was assumed to be the same as the intake measured from a physiological experiment conducted with cows from the same herd offered fresh cut grass ad libitum and similar concentrate supplementation as in this experiment (Sairanen et al. 2005). The net herbage production was estimated to be the same as grass intake from the above mentioned experiment (Table 5).

Herbage allowance (HA) per cow is an important factor in pasture N cycling. Increasing HA usually increases herbage intake (HI), but at the same time more herbage mass (HM) is left in residual mass due to the diminishing return relationship between HA and HI (Johansen and Hoglind 2007). When large amounts of rejected areas are left, the sward will quickly deteriorate due to accumulation of old leaves, stems and reduced tiller numbers (Chapman and Lemaire 1993). If maximum HI is desired, HA must be so high that HM utilization (measured from soil surface) will drop below 50 % (Johansen and Hoglind 2007). However, increasing HA did not increase milk production either in the experiments of Virkajärvi et al. (2002a) or Johansen and Hoglind (2007).

The higher the HA is, the less cows there will be per hectare and thus less N will be recycled through dung and urine. At the same time more N will be recycled through decomposing sward fractions. In environmental terms large HA seems a better alternative, as evenly distributed, slowly mineralizing N from decomposing grass should be more effectively used in grass regrowth than spatially distributed urine N applied in very high doses.

There could also be a difference in animal intake between pure grass and grass-clover pastures. In some studies N intake of grazing animals has been better on mixed grass-clover swards (Thomson 1984; Harris et al. 1997; Phillips and James 1998; Phillips et al. 2000). In contrast, Ribeiro Filho et al. (2005) could not find any difference in animal intake between pure ryegrass and ryegrass-clover mixture. This was also the case in EXP III, where the post grazing sward height and the proportion of rejected herbage was equal between pure grass and grass-clover swards (Table 5).

The watering facility area functions as a cattle congregation area and if the stocking rate is high, it receives a large amount of excretal N and suffers treading damage that destroys the vegetation. As a result, the area around the watering facility acts as a point source for N leaching on pasture (EXP II and III). During warm weather, cows tend to spend more time near the water supply and this also increases excreta deposited on that area (White et al. 2001).

Herbage production of the silage cut plots in EXP II was 8900 kg DM ha^{-1} y^{-1}, which is average for Finnish fields. For the grazed plots, the gross HM production was 7000 kg DM ha^{-1} y^{-1}. Pre- and post-sward heights were within the recommended limits for Finnish pastures (Virkajärvi et al. 2002) and the amount of infrequently grazed area was less than 35 % in both years (Table 5). The N concentration of grazed and cut herbage was typical for intensive production systems (McDonald et al. 1995). The higher N content of pasture is basically a consequence of the younger stage of HM. This is relevant for leaching, since it affects the N partitioning between dung and urine.

In EXP III the gross HM production was much higher than in EXP II (Table 5). Grass and grass-clover pastures did not differ statistically from each other during the experimental years, although there was a clear decrease in the HM production of the grass-clover pastures in the third year (Table 5). The average N content of the herbage DM was also similar in both treatments. The N content of both treatments increased over the experimental years and the milk N content followed the same pattern. The yearly mean clover proportion (mainly white clover) of the grass-clover pasture was 49 %, 47 % and 76 % in 2001, 2002 and 2003, respectively. There were no differences in herbage production between the treatments in the renewal year.

The gross HM production of both pastures was high compared to previous grazing studies (Kuusela 2004a; Virkajärvi 2004) . The main reason for the high productivity was the rotational grazing system, as the grazing took place nearly at the optimum grazing stages. It is also likely, that there was a residual effect of EXP II (dung) that was at the same lysimeter field two years prior to the start of EXP III.

The difference between the fertilized grass and unfertilized grass-clover pasture was smaller than expected. In HM production during grazing years the grass-clover pasture yielded 8 % and in energy corrected milk yield (ECM) 9 % less than the grass pasture. However, the total N yield of the whole ley rotation was only 4 % lower for grass-clover than for grass pasture. Usually clover-based systems yield at least 20 % less than fertilized grass systems (e.g. Frame and Newbould 1984; Ruz-Jerez et al. 1995). The reason for the high HM yield of the grass-clover pasture was the high proportion of clover that was well above that obtained in an experiment in organic farming in Finland (19 – 47 %; Kuusela 2004a). In our experiment, the growth of white clover was favoured by rotational grazing with 3–4-week intervals (e.g. Menneer et al. 2003), a favourable soil type (fine sand with good water capillarity), companion grass with weak competition ability and a short ley rotation (3 years) that prevented the pasture from suffering ‘clover crash’ (Frame and Newbould 1984).

Table 5. Grazing management parameters in experiment II and III.

	Exp II		Exp III					
	1998	1999	2001		2002		2003	
	grass	grass	grass	clover	grass	clover	grass	clover
Gross DM production kg ha^{-1}	6020	7940	11620	12010	12670	12230	12460	9920
Net DM production kg ha^{-1}	4050	5170	7149	7018	6843	7003	7338	5649
N content g kg^{-1} DM	37.3	36.1	26.0	23.7	31.2	29.4	35.0	35.7
Sward height (cm) before grazing	26	27	32	31	27	25	25	22
Sward height (cm) after grazing	11	11	10	11	10	9	9	9
Rejected area %	22	20	14	19	17	14	13	17
DM allowance kg DM cow^{-1} d^{-1}	23	23	25	25	25	25	25	25
LU ha^{-1}y^{-1}	278	355	491	482	470	481	504	388
Average milk production kg cow^{-1} d^{-1}	19.0	24.8	27.6	27.9	26.3	28.2	24.9	28.0
Energy corrected milk production kg ha^{-1}	5340	8810	13890	12800	13680	13340	12580	10500
Dung pats ha^{-1}	nd	4780	5200	5000	5150	5960	5080	4150
Dung coverage %	nd	3.7	4.1	3.9	4.0	4.7	4.0	3.2

3.2 The treading damage of pasture soil

Trampling by animals causes soil deformation through soil compaction by the high-ground pressure of hooves and soil homogenisation by shear effects especially on cattle congregation areas (Warren et al. 1986). The effect of grazing on soil penetrability and pore structure was clear even on freely drained light mineral soil as in this study (Fig. 5) and the effect was even worse on heavy clay soil (Pietola et al. 2005).

There was a significant difference between pure grass and grass-clover mixtures in soil compaction, pure grass being more severely compacted than clover mixture with almost the same stocking rate (Fig 5.). This was probably caused by clover roots, which were visibly larger than grass roots in upper soil and thus had a softening effect on soil in 4-14 cm layer.

Use of clover in grazed grass mixtures could also have a positive effect on soil structure and drainage on finer textured soils. Better drainage could lead to increased nitrate leaching but in this study the N leaching from unfertilized clover swards was less than from N fertilized swards and was low.

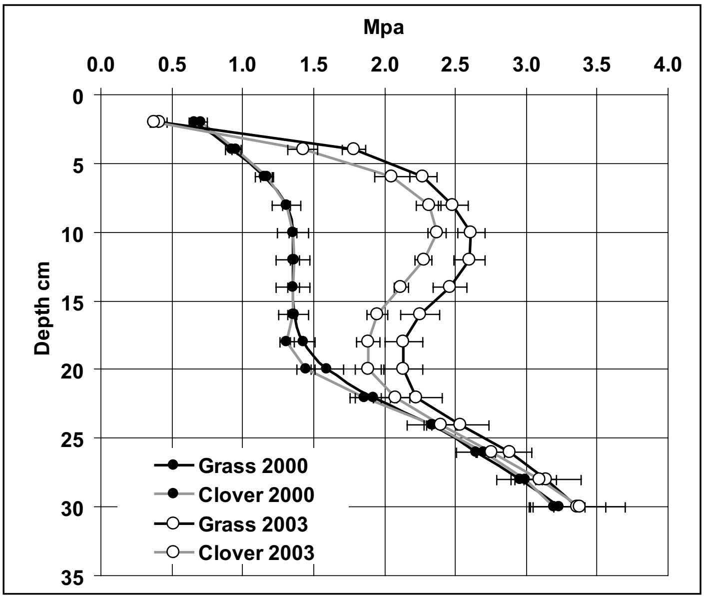

Figure 5. Change in freely drained light mineral soil penetrability from the beginning of grazing in autumn 2000 to the end of it in autumn 2003. The difference between the grass-clover mixture (clover) and pure grass pasture in autumn 2003 is significant ($p < 0.05$) from 4 to 14 cm depth.

3.3 N inputs to the pasture system during the grazing years

Total N inputs in pasture systems depend mainly on the intensity of pasture production. Amount of fertilizer, legume use, stocking rate and supplementation are most important input variables. In the EXP II and III the intensity of grazing differed because of the productivity of the sward. In EXP II grazing started when the sward was already three years old and lasted for two years. Furthermore, the study area had never been used as a pasture before and this increased the capacity of the soil to retain excess N.

In these experiments the total N content of the soil to 60 cm depth was 14 400 kg ha^{-1} (std 2000 kg N ha^{-1}), which is near the upper limit of 5-15 t N ha^{-1} scale presented in the review of Ryden (1984). As the total N content of the soil was rather high there was potential for net N mineralization from soil in addition to other N inputs.

3.3.1 Fertilization and atmospheric deposition

The total amount of fertilizer N recommended in Finland is within the range of other countries that rely mostly on fertilized pure grass swards (in New Zealand white clover is important) (Table 6). However, when related to the length of the grazing season or livestock units per grazing day (LUGD), the Finnish recommendation is high.

The N fertilizer use on actual farms is 176 kg N ha^{-1} y^{-1} which is 14 kg less than the new recommended rates (Virkajärvi 2005). The same phenomenon can be seen in both in Ireland and the UK, where the recommended rate is rather high, but the actual use of artificial fertilizer N is much less. In the UK the N use is 89 (Anon. 2003 ref. Cuttle et al. 2004) and in Ireland 176 kg N ha^{-1} y^{-1} (Coulter and Dillon 2002). In addition, according to the British Survey of Fertilizer Practice, 29 % of the all grasslands in England and Wales received no N fertilizers and only 5 % of grazed and 15 % of cut grassland received more than 250 kg N ha^{-1}. However, instead of artificial fertilizers, 66 % of the silage area received N from slurry or solid manure (Anon. 2003 ref. Cuttle et al. 2004).

The length of the grazing season changes due to climatic conditions. Therefore, a better way to compare N fertilizer use is to calculate N fertilizer use per length of the grazing season or livestock unit grazing days per hectare. Based on these calculated ratios the Finnish recommendation is one of the highest among the listed countries (Table 6).

Table 6. Used or recommended N fertilizer amounts from Finland, Sweden, Denmark, UK, Ireland and New Zealand. (LU = livestock unit, GD = grazing days, LUGD = livestock units * grazing day)

	Annual N use kg ha^{-1}	LU ha^{-1}	GD $season^{-1}$	kg N per GD	kg N per LU*GD	ref
Finland	220	3	110	2.0	0.67	11
Finland (new)	190	3	110	1.7	0.58	10
Sweden	200	3.8	138	1.4	0.38	3,6
Denmark	300	5	138	2.2	0.43	8
UK	350	3.6	168	2.1	0.58	7
UK, (NVZ)	250	2.6	168	1.5	0.57	1
Ireland	390	3.45	226	1.7	0.50	5
New Zealand	150	3	360	0.4	0.14	9,3,4

1. Andrews et al. 2007 (NVZ = nitrate vulnerable zone) 2. Dairy Base® Economic survey 2005-2006. 3. Frankow-Lindberg et al. 1992. 4. Hodgson 1990. 5. IFI and Teagasc. 6. Mangnusson and Bursted 1992. 7. Mayne et al. 2000. 8. Søegaard et al. 2001. 9. Thom 2000. 10. Virkajärvi, 2005. 11. Virkajärvi et al. 2002b

Atmospheric N deposition in precipitation in Central Finland is less than 5 kg N ha^{-1} y^{-1} (Vuorenmaa et al.2001) thus it is of minor importance in N cycling.

3.3.2 Supplementation and diet N concentration

In both EXP II and EXP III cows were fed cereal based concentrates in addition to herbage. This is a common practise in Finland, as high production levels are desirable. In EXP II the cows production level was lower than in EXP III, so the amount of concentrates was also lower (4.2 and 4.5 kg DM day^{-1} which equates to 26.2 and 35.8 kg ha^{-1} N in 1998 and 1999, respectively).

It could be assumed, that the higher the milk production potential of the cow, the higher the N utilization from the pasture sward. This is true only if high producing cows are not fed concentrates or the used concentrates have a low N concentration like maize silage (Steinshamn et al. 2006). However, in cool regions such as most of Scandinavia, maize can only be grown to a limited extent and thus, cereal based concentrates are used. Even though feeding the high energy – low protein content concentrates improves the N utilization in milk production, it decreases the pasture sward intake by replacing (substitution rate) some of the grass that would have been eaten without concentrate addition in the diet. In these experiments the substitution rate of used concentrates was 0.5, which means that for every kg concentrates 0.5 kg pasture DM was rejected. In EXP II this substitution rate equalled 630 and in EXP III 1290 kg pasture DM ha^{-1} y^{-1}.

In Finland it is common practice to use protein supplementation (rape or soya meal) in addition of cereal based concentrates (Sairanen, personal comm.). This may increase milk production (Khalili et al. 2002), but certainly lowers N yield from the pasture sward. In EXPII and III with average amount of concentrates, the apparent recovery of concentrate N in milk production was 73-100 % calculated from the annual mass balance data (Table 9, 10; Section 3.5 N Balance). This means that milk N yield from pasture was only 0 - 20 kg N ha^{-1} y^{-1}. High milk production can be achieved also without protein supplementation (Peyraud et al. 1996; Kennedy et al. 2003; Wilkins et al. 1994) and from an environmental point of view this should be encouraged.

When the whole diet is considered, most of the ingested N is excreted in dung and urine and only a small proportion is converted into milk. Thus the amount of excretal N returns depends on the grazing pressure and supplementation. The N content of herbage fed to the cows affects the proportion of N excreted in urine and dung. However faecal N excretion varies little with the dietary composition, but urinary N varies more with an excess of ingested protein and a lack of equilibrium between protein and energy (Vèritè and Delaby 2000). Thus, N fed in excess of animal or rumen requirement will essentially be excreted in urine (Steinshamn et al. 2006). N in urine is mainly in a soluble form, which is vulnerable to leaching whereas dung N is mostly in stable, organic forms (Whitehead 1995).

The proportion of dung and urine patches that cover the total pasture area is dependent on stocking rate. The supplementation and stocking rate (SR) have a marked interaction on the N cycling in pastures. With high stocking rate and concentrate supplementation, nitrogen input from concentrates may exceed the N output in milk, thus increasing the N returned to the pasture, in addition to the N applied in fertilizers. In EXP III this was almost the case (Table 7).

Table 7. Sward net HM production estimated based on the DM intake measured from a physiological experiment conducted with similar cows offered fresh cut grass ad libitum and equal concentrate supplementation as in this experiment (Sairanen et al. 2005). Measured grass intake was 14.6 kg DM cow^{-1} d^{-1} and concentrate intake 5.4 kg DM cow^{-1} d^{-1}. Yearly N intakes (kg ha^{-1}) were calculated from grazing days per hectare.

	Exp III							
	2001		2002		2003		Mean	Mean
	grass	clover	grass	clover	grass	clover	grass	clover
Grass DM intake kg ha^{-1} y^{-1} (net HM production kg ha^{-1} y^{-1})	7149	7018	6843	7003	7338	5649	7110	6557
Grazing days LU^{-1} y^{-1}	491	482	470	481	504	388	488	450
Grass N content %	2.60	2.37	3.12	2.94	3.50	3.57	3.07	2.96
N from grass kg ha^{-1} y^{-1}	186	166	214	206	257	202	219	191
N from concentrates kg ha^{-1} y^{-1}	67	66	65	66	69	53	67	62
Total N intake kg ha^{-1} y^{-1}	253	233	278	272	326	255	286	253
N in milk kg ha^{-1} y^{-1}	70	69	67	71	69	58	69	66
N in urine kg ha^{-1} y^{-1}	103	91	119	113	146	112	123	105
N in dung kg ha^{-1} y^{-1}	55	49	64	61	79	60	66	57
N utilization in milk production %	28	30	24	26	21	23	24	26

3.3.3 Soil N mineralization-immobilization turnover

In the field the mineralization of N from soil organic matter occurs partly from recently-added plant and animal residues, partly from more humified material and partly from turnover of microbial biomass (Whitehead 1995). In short ley rotations it is typical that N is immobilised during the grass cover years and mineralized following ploughing every three years (Hatch et al. 2003) (Fig. 6).

According to Zaman et al. (1999) and Jones et al. (2004) soluble (SON) and dissolved organic N (DON) act as important components in the mineralization process. However, this fraction is rarely measured in soil extracts, even though in the literature SON is described as an important factor that should be routinely included when measuring mineral nitrogen pools in soil (Murphy et al. 2000; Jones et al. 2004). In present study, the proportion of SON in fertilized grass pasture soil accounted for 90 % of the total soluble N (TSN) in soil, when the fertilizer effect was not included. Comparable figures have been found from or-

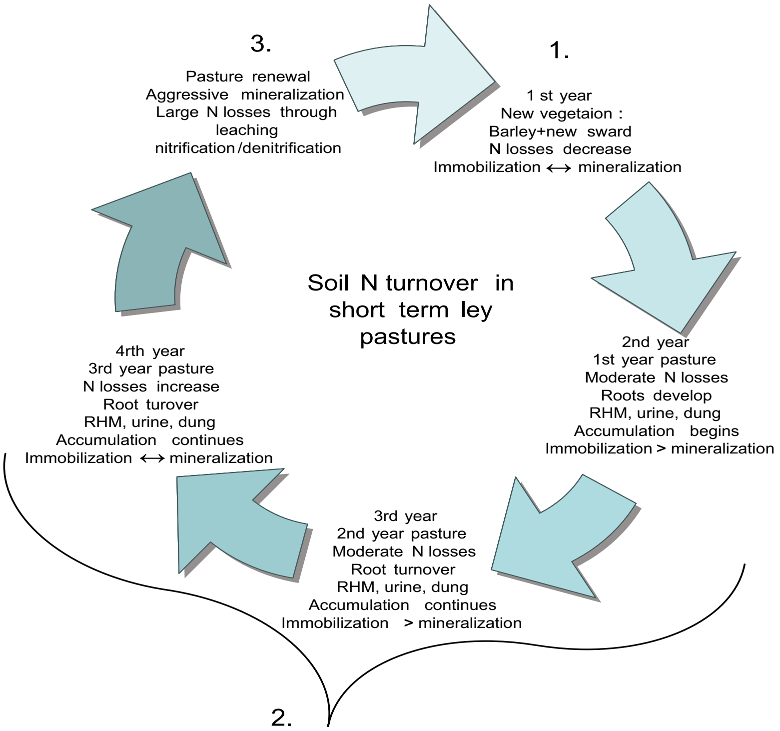

Figure 6. N turnover in the soil underneath the fertilized grass pasture in EXP III as an example of N mineralization during one pasture ley rotation. 1. First year after renewal of the EXP II sward 2. Pasture years and 3. Renewal year of EXP III. (RHM = rejected herbage mass)

ganic clover-grass swards (Murphy et al. 2000). The amount of soluble organic N in the soil measured to a depth of 60 cm remained fairly constant (60 kg N ha^{-1}) throughout the experiment. Thus, if this pool is involved in mineralization reactions the organic matter N transformation rate to and from the SON pool must be nearly equal.

1. First year after renewal of the EXP II sward (Fig. 6)
At the end of EXP II (1999) the 5 year old sward was destroyed in the autumn by glyphosate spraying followed by ploughing in the next spring. The estimated amount of N in the vegetation (1500 kg DM ha^{-1} with 3 % N content) and root system (estimate 5000 kg DM ha^{-1} with 1.6 % N content) of old grazed and cut plots was 125 kg N ha^{-1}. In the grazed plots there was also a substantial amount of N immobilized from dung and urine. An estimate of total N immobilization is the sum of N not accounted for in the N balance. This was approximately 370 kg ha^{-1} for pasture during two experimental years. However, this amount includes N in surface runoff, ammonia volatilization and denitrification, so the actual quantity of N immobilized was likely to be considerably smaller. In the cut plots the balance was negative, indicating net mineralization of N from soil during the experiment.

The new grass was sown with barley as a cover crop without extra N fertilization, so all the N bound in HM was originated from mineralization of organic matter in the soil. Unfortunately, the N yield of barley (harvested as whole crop from previously cut and grazed plots) was not measured separately for the two treatments during the renewal year. The N yield from the whole area was 90 kg N ha^{-1}, which represents 24 % of the pasture balance excess. In the experiment of Eriksen (2001) barley yield after renewal of grazed and cut plots was 60 kg N ha^{-1} larger from the grazed treatment. In EXP II nitrogen leaching after the destruction of the sward was significantly higher from grazed plots than from cut plots suggesting higher mineralization in the grazed plots compared to cut plots, supporting the findings of Eriksen (2001).

Nitrogen bound in barley roots and stubble was also available for mineralization after the barley was harvested as a whole crop in July. Malhi and Lemke (2007) report 700-800 kg barley root DM ha^{-1} which corresponds to 11-14 kg N ha^{-1}. The estimated amount that growing grass could have taken up in the shoots (1500 kg DM ha^{-1}) and roots (1300 kg DM ha^{-1} according to Crush et al. (2005) root:shoot ratio 0.86) during the period from July to the end of the growing season was 60 kg N ha^{-1}. As the amount of N bound in grass is fairly small, the rapid decrease in N leaching from the area during the following autumn, winter and spring suggests that the N mineralization rate must also have decreased markedly. The results from the literature support this (Eriksen 2001).

Altogether, the total amount of N mineralized from cut and grazed plots during the renewal year was at least 162 and 196 kg N ha^{-1}, respectively. Some N must have been lost by denitrification that is known to increase when old swards are destroyed due to the extra carbon and nitrogen supply in the soil. The losses of N in surface runoff and ammonia volatilization were of minor importance after ploughing the soil.

2. Pasture years (Fig. 6)

According to Eriksen (2001) and Mitchell et al. (2001) the mineralization of organic matter continues for at least two years after sward destruction but the mineralization rate slows down considerably. So, some residual effect must have been left in the soil at the beginning of EXP III. However, the NO_3N -concentration in leachate was low (< 5 mg l^{-1}), so the mineralization rate must have been slow. The N mineralization-immobilization equilibrium changes as a grass sward ages. Accumulation of organic N under grassland is approximately linear in the early years of renewed grass leys (Tyson et al. 1990).

In the beginning of first pasture year, N supply for the grass comes mainly from the N fertilizer, as the excretal returns have just started and during first grazing rotations cover only a small proportion of the whole area. Nitrogen bound to the grass root system is usually assumed to be the same at the beginning and end of the growing season, as the same amount of N is mineralized from dead roots as bound again to produce new ones. However, the grass root system of young grass probably still binds N before the equilibrium turnover starts.

As mentioned previously, N immobilized from excreta in addition to fertilizer N is an important mineralizable N source at pasture. The sum of N returned to the pasture in dung and urine was 198 and 368 kg N ha^{-1} during three grazing years, respectively. High excretal N returns to pasture show no relationship to N fertilizer requirement in the short term due to the low utilization of excreta N (faeces 7%, urine 19%; EXP I). Knowing the distribution of the dung pats (Fig 7.) and urine patches (White et al. 2001), the ability of soil fauna to carry dung dry matter from the pat to surrounding soil and the slow mineralization rate of dung N (e.g. Holter 1979; Wachendorf et al. 2005), a large amount of excretal N was immobilized in soil organic matter pool during the grazing years.

The average amount of N not accounted for in the EXP III nitrogen balance during grazing years was 106 kg N ha^{-1} y^{-1} (Table 10). In EXP III the N losses in measured surface runoff and ammonia volatilization and the estimated denitrification were included, so the residual N should be a good estimate of immobilized N. According to Watson et al. (2007) the amount of N accumulated in soil varied between 102-152 kg N ha^{-1} y^{-1} in pastures grazed with beef steers and fertilized with 100-500 kg N ha^{-1} y^{-1}, respectively. Tyson et al. (1990) measured 75 kg N ha^{-1} y^{-1} accumulation in the early years after sowing a new sward. Altogether there was approximately 330 kg N ha^{-1} immobilized in the soil, shoots and roots in the autumn before ploughing in the following spring in EXP III (Table 8; the amount of N in roots is recalculated based on the actual analysis of the root DM nitrogen concentration)

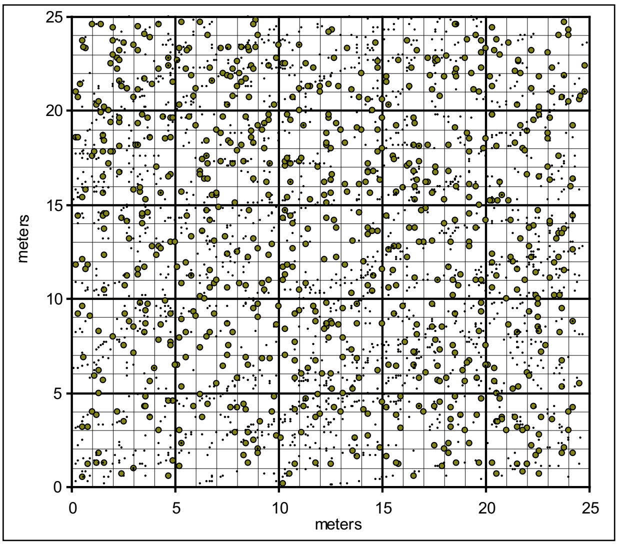

Figure 7. Dung coverage (16 % of the total surface area, no overlap taken into account) on grass pasture after three grazing years (1465 grazing days ha^{-1}) on one experimental plot (lysimeter 5) in Exp III. Large spots represent a full dung pat and small spots represent less than a half of a dung pat determined visually.

Table 8. Soil mineral N content to 60 cm depth, aboveground grass shoot and root DM and N content to a depth of 15 cm in Exp III. SE in parenthesis.

Grass	DM kg ha^{-1}	N %	kg N ha^{-1}
Soil NO_3N + NH_4N			47
Grass shoots	2390 (199)	3.2	76
Grass roots (0-15 cm)	5050 (1558)	1.6	81
Sum			204

3. Renewal of the EXP III sward (Fig.6)

The sum of the N outputs after renewal in EXP III (247 kg N ha^{-1}; Table 10, Section 3.4) exceeds the sum of N found in above-ground vegetation, roots and soil in previous autumn by 43 kg N ha^{-1}. This indicates that there must have been substantial mineralization from soil organic matter to support the root growth of the first year ryegrass and barley. The root system of ryegrass alone to a depth of 20 cm required 40 kg N ha^{-1} in the experiment of Eriksen et al. (2004). Some N was probably also lost in gaseous form as denitrification is enhanced by ploughing (Davies et al. 2001).

There was no difference between N yields of barley and annual ryegrass from fertilized grass pasture and unfertilized grass-clover pasture, so the amount of mineral N available for new vegetation must have been adequate. This conclusion is based on the fact that there was a significant difference in the amount of N leached between fertilized grass and unfertilized grass-clover pastures during the renewal year, showing that N mineralization must have been greater in the fertilized grass pasture than in the unfertilized grass-clover pasture (Table 10, Section 3.5 N Balance).

The cumulative effect of two consecutive pasture rotations on some lysimeter plots was clearly visible in the amount of leached N (Fig 8, Section 3.3.4 Leaching and surface runoff). This suggests that some residual effect was still remaining in the soil from EXP II after a whole ley rotation in EXP III and this N was mineralizing after ploughing of the EXP III sward (balanced acros the treatments in EXP III). In continuously changing management conditions, as in short term ley farming, the soil N will never reach the equilibrium state with balanced N inputs and outputs that is typical for long term or permanent pastures. In ley farming the soil N is in a constant state of change as Stapledon (1935) observed many years ago.

Estimate of mineralization based on zero fertilized plots

The potential of the soil to support grass growth without N fertilization (zero fertilized plots) gives an estimate of the amount of mineralized N. Even though the amount of leached N was low in the beginning of the EXP III, the residual effect of previous sward was clear in zero fertilized plots. The N yields harvested to 10 cm stubble from the unfertilized plots without grazing was 90 (SE 9.5), 64 (SE 2.2) and 47 (SE 2.7) kg N ha^{-1} y^{-1} in first, second and third pasture year, respectively. Dry matter N yield represented 0.8 -1.5 % of the soil total N content to 25 cm depth.

These numbers do not include N cycling caused by grazing (excreta and rejected grass), so they are not directly comparable with pasture soil N mineralization, as grazing changes the soil microbial community (Attard et al. 2008) and affects the mineralization rate in many different ways (soil compaction, plant residues, excreta).

Furthermore, cut herbage DM was removed from the zero fertilized plots in synchrony with grazing rotations on grass treatments on the lysimeter field. Thus the organic material, which is the source of further mineralization in the following year, was decreased every year. This was reflected in yearly diminishing N yield. Due to the above reasons, the use of zero fertilized plots to estimate the N mineralization at pasture is unreliable and not recommended on long term pastures. If it is never the less used, it should be taken into account that the N yield from these plots is probably increasingly underestimated year by year.

3.3.4 Symbiotic N fixation (SNF)

White clover proportion increased in the sward during the experimental years from 49 to 76 % of the DM per year. Reasons for surprisingly high clover growth in this experiment are discussed in detail in paper III. White clover survival in the sward depends on the soil P and K status (Bailey and Laidlaw 1998), cutting regime, sufficient water supply and stolon survival over winter. The role of the companion grass for clover persistence is also significant. Aggressive grass varieties can severely suppress clover growth (Rhodes et.al. 1987). Timothy and meadow fescue mixtures are weaker competitors compared to perennial ryegrass.

The N input of a grass-clover pasture is mainly dependent on the SNF of the clover component of the sward, but estimating the amount of SNF is difficult. As we did not measure the clover SNF, an estimate was calculated based on the clover content of the sward, and the proportion of SNF-N in the clover N (Jørgensen and Jensen 1997; Høgh-Jensen and Schjoerring 2001) This method is unreliable as the net growth of the sward between grazing rotations was not measured and thus the SNF was calculated for gross DM growth, which overestimates the fixed amount of N. However, large amounts of N are channelled into the clover root system. Some of this fixed N is then transferred to the soil in the form of decomposing roots, nodules and rhizodeposition.

Another way to estimate the amount of N fixed is described by Høgh-Jensen et al. (2004). This model takes into account N transferred to roots and soil and the effect of grazing animals on SNF efficiency and thus, it is a more reliable estimate of total symbiotic N_2 fixation of the sward.

The amount of net DM production of the grass-clover mixture is presented in Table 7. The proportion of clover in the sward was 47, 49 and 76 % in first, second and third pasture year, respectively. The N content of the white clover component of the mixed sward was measured only during the third grazing year (3.79, 3.71, 3.57, 4.17 and 4.86 % for grazing rotation 1, 2, 3, 4 and 5, respectively). The weight corrected mean (3.95 %) based on HM net production was used to estimate the N fixation of the first and second year also.

The total amount of SNF using the formula of Høgh-Jensen et al. (2004) was 212, 226 and 210 kg N ha^{-1} y^{-1} during the first, second and third pasture year, respectively. The variation in measured N_2 fixation for white clover in ryegrass mixtures varies from 1 to 545 kg N ha^{-1} y^{-1} (see the review of Carlsson and Huss-Danell 2003).

The proportion of white clover in mixed ryegrass–white clover swards is known to decrease, especially in urine patches, as ryegrass makes more effective use of soil mineral N. However, the effect is caused by an increase in the number of ryegrass tillers, not directly by decreasing the number of clover stolons (Vinther 1998; Menneer et al. 2003).

It is known that the main grasses in our grass-clover mixture, meadow fescue and timothy, are weaker competitors than ryegrass in intensive grazing conditions and especially in urine patches with high N concentrations (Gooding and Frame 1997; Vinther 1998). Furthermore, the tiller density of the timothy-meadow fescue mixture is low (2000-5000 tillers m^{-2}; Virkajärvi 2004) compared to that of ryegrass (10 000-18 000 tillers m^{-2}; Gooding and Frame, 1997), and the growth pattern of the timothy-meadow fescue sward is open, which gives the clover stolons more space to develop, compared to a ryegrass mixture. In these circumstances, the strong white clover variety AberHerald, which is known for its winter hardiness, fast spring growth ability and high dry matter yield (Nykänen-Kurki and Rönkä 1998), was able to increase its proportion in the sward.

3.4 N outputs from the pasture system during the grazing years

3.4.1 Milk and excretal N deposited during milking

In EXP II and III milk N was the largest N output from pasture during the grazing years. Rotational grazing probably enhanced milk production, as the area was grazed at optimum grazing state. This is not the case in real life farming, but sometimes grass gets too tall or is too short to be grazed and this decreases milk production temporarily. As mentioned above (Section: Grazing management) decreasing HI affects the partitioning of N on pasture. If a large amount of N is ingested, more N will be deposited in urine and cycling is more intense than if large amounts of N are left in rejected areas that decompose between rotations and during winter and spring.

The breeding target is usually high producing individuals that have an efficient nutrient turnover to milk (Dillon et al. 2006). However, there is evidence that genetically high production animals (American Holstein-Friesian) can not express their full production potential using only grass for milk production and in addition they will suffer from energy deficiency. That is because they have been bred in conditions where selection has been based on production potential with high concentrate intake (Kennedy et al. 2003). This encourages the use of large amounts of concentrates during the grazing season, which decreases the N utilization of pasture grass. Horan et al. (2006) suggest that in the future breeding should take their environment into account when selecting cows for different purposes (e.g. for pasture or concentrate dominated diets).

When calculating the mass balance for pastures, it is essential to take into account the amount of N deposited during milking time. Depending on circumstances, cows spend more than 20 % of their time during the day in milking parlour, thus the dung and urine excreted during this time is not carried back to the pasture area. Cows usually defecate more when they are stressed (Friend 1991) and moving in and out of the milking parlour or cow house may be stress inducing situation and thus increase the proportion of dung deposited to the lanes and parlour compared to pasture. However, when cows are handled calmly and gently they get used to these events and remain calmer (White et al. 2001). According to White et al. (2001) the amount of dung and urine excreted in lanes and milking parlours was highly correlated ($r > 0.90$) with the time spent in those areas. Results of Oudshoorn et al. (2008) also support this even though they have not measured excretion indoors. In these experiments (II and III) the amount was nearly equal to N excreted in milk (Table 9, 10).

3.4.2 Nitrogen retention in pregnancy

Most of the placenta grows during the first two thirds of pregnancy (MacDonald et al. 1995). In contrast, over 60 % of foetal growth occurs during the last two months of the pregnancy (Van Saun and Sniffen 1996). Nitrogen retention in tissues involved in gestation (foetus, placenta, uterus and mammary gland) was estimated based on values from literature. Average newborn Holstein-Friesian calf weighs 45 kg (Bell and Roberts 2007) of which 1.3 kg is N (Rastas et al. 1989; MacDonald et al. 1995). Other tissues involved in pregnancy were estimated to contain 1.6 kg N per cow (MacDonald et al. 1995).

In EXP II the amount of N detained in gestation was not estimated. In EXP III 30 % of the cows were over 5 months pregnant, so N retention was calculated for this proportion only. Stocking rate was 4.45 cows ha^{-1} y^{-1} so the total amount of N taken up by pregnant cows was 3.8 kg N ha^{-1} y^{-1}. The amount is less than 6 % of the milk N output from pasture. In addition, some of the cows were in early stages of lactation and losing weight, so the meaning of N detained in grazing cows tissues was modest.

3.4.3 Ammonia volatilization

NH_3 emission is dependent on the soil pH, moisture, texture, cation exchange capacity (CEC) and temperature, as well as on the wind speed and air temperature (Bolan et al. 2004). The N concentration and hippuric acid content of urine are also important factors (Petersen et al. 1998). The total emission from the pasture was 16.1 kg NH_3-N ha^{-1} y^{-1} when the relative % coverage of dung and urine was taken into account. Approximately 96 % of the total emission originated from urine. In the present experiments the emitted NH_3-N was on a moderate level (1–17 % of applied N) compared with the large variation in the literature (3–52 %) (Sherlock and Goh 1984; Ryden et al. 1987; Whitehead and Raistrick 1993; Petersen et al. 1998).

However, there was a large difference between the experiments in the total amount of volatilized NH_3-N. Overall, the level of volatilization from the control treatment in part study 2 was only half that of part study 1. As the soil pH, CEC, air temperature and rainfall were comparable between the experiments, the reason for the difference in the amount of volatilization could be in the soil parameters. In part study 1 the soil was dry, even hydrophobic (soil volumetric water content ca. 10 %) when applying the treatments. In part study 2, the soil volumetric water content at the beginning of the measurements exceeded the maximum water holding capacity measured from the same area by Pietola et al. (2005).

Heavy rainfall is known to diminish NH_3 volatilization (Bussink 1996; Whitehead and Raistrick 1991). However, light rainfall (< 5 mm) has increased NH_3 volatilization (Bussink 1996). In the present study irrigation of 5+5 mm reduced the NH_3 volatilization by 46 % and 20 mm by 75 %.

The dynamics of NH_3 volatilization were well in line with previous research. Over 80 % of the total emission occurred during the first 48 h and a clear diurnal rhythm of volatilization was observed. Increasing rainfall markedly decreased NH_3 emission. The most important factor explaining the differences in volatilization in this experiment was the combination of soil moisture content and soil temperature. Volatilization was highest with dry and warm soil. The JTI method appeared to be applicable for measuring NH_3 volatilization from simulated urine and dung patches.

Compared with our results, some of the previous national NH_3 emission estimates of Finnish pastures are overestimates. Keränen and Niskanen (1987) used the results of Buijsman et al. (1987) and estimate that 5 % of the dung N and 40 % of the urine N are volatilized during grazing. Pipatti (1990) gives a figure of 6.5 kg NH_3-N y^{-1} cow^{-1} during the grazing season, while our result 16.1 kg NH_3-N ha^{-1} transforms to 4.0 kg NH_3-N y^{-1} cow^{-1} when divided by an average stocking rate of 4 cows ha^{-1} y^{-1}. Based on these results, the volatilization of NH_3 from pasture is of minor importance and grazing needs little attention as a source of NH_3 emission in Finland.

3.4.4 Nitrification and denitrification

At pasture, soil organic N and dung and urine N convert to NO_3-N in nitrification and continue in favourable conditions through denitrification or chemo-denitrification to N_2. Nitrogen losses through denitrification are usually larger that from chemo-denitrification or nitrification (Granli and Bøckman 1994). There are two major factors effecting the gaseous N emissions from soil. One is the denitrification rate and the other one is the ratio between the N_2, N_2O and NO_x originating from the microbial processes involved in nitrification and denitrification reactions (Weier et al. 1993; D'Haene et al. 2003).

Denitrification is dependent on soil texture, and generally occurs if the water filled pore space in soil exceeds 60 % (Aulakh et al. 1991; 1992) and the rate tends to increase with increasing soil water content (e.g. Weier et al. 1993; Ledgrad et al. 1999). Denitrification strongly depends on soil NO_3^-N concentration and on the availability of organic C such as soil organic matter, crop residues and green manure. Field studies also show an increase in denitrification rate with increasing fineness of soil texture (Aulakh et al. 1992). In the present study, the hot-spots of N dynamics are urine patches and dung pats that cover annually 17 and 4 % of the whole pasture area, respectively. Excretal N and C act as sources for denitrification and at least part of the time there must have been anaerobic sites in the soil underneath urine patches that promoted denitrification.

There was also a simultaneous experiment on N_2O and NOx emissions from dung and urine and clean grass and clover mixture pastures during 2002-2003 on the same experimental area as in EXP I, so a brief description of those results is presented here. Detailed presentation of the experiments and part of the results are given in Maljanen et al. (2007). The rest of the results are from Virkajärvi et al. (unpublished).

The total amount of N lost in the form of N_2O during one year measured using the closed chamber technique was 3.1-6.9, 9.9-63.4 and 1.3-3.9 kg N ha^{-1} from urine, dung and clean grass pasture, respectively. The N_2O emissions related to the surface coverage of excreta for fertilized grass pasture was 3.2-4.1 kg N ha^{-1} and for the unfertilized grass-clover pasture 6.4-7.6 kg N ha^{-1}. The value for the whole fertilized pasture area was 1.3 % of the total N input (including fertilizer N and concentrate N), which is low compared to other studies reported in the literature, 2.1-6.7 % (Velthof et al. 1996), 2.0-2.5 % (Saggar et al. 2004) and 2.7 % (Luo et al. 2008). The N_2O emissions during winter through up to 50 cm deep snow cover were as high as during summer. The temperature at the soil surface under the snow pack was near zero through the winter, even when the outside temperature reached -30° C degrees. Thus, soil microbial reactions were slow but still functional, which explains the winter emissions (Dorland and Beauchamp 1991). In fact, several studies have shown that winter time emissions of N_2O from boreal agricultural soils, related to freezing and thawing cycles, may account for more than 50% of annual N_2O emissions (e.g., Maljanen et al. 2003; Regina et al. 2004; Syväsalo et al. 2006;). The overall level N_2O emission from pasture was lower than estimated in the IPCC (2001) report.

In EXP I, the nitrification of urea in urine started 3 days after urine application and proceeded fast, as most of the urine N was in the NO_3-N form 21 days after application. During the main nitrification period from 10 to 21 days after application, 29 % (25 kg N ha^{-1}) of the urine N was lost. The rainfall during the period was low and soil dried, thus it is likely denitrification and leaching losses during this period were small. This is well in line with the study of Maljanen et al. (2007), who reported that dry and warm soil enhance NO emissions, which suggests that in these conditions nitrification is the dominant reaction in the soil. Immobilization is the most probable explanation for the loss of N. For example Williams and Haynes (1994) have measured immobilization of added N as high as 20%, during the first 24 h after urine deposition using a ^{15}N technique.

The total amount of denitrified N estimated from the ratio between N_2/N_2O is not recommended, as it depends on several different parameters in soil and can range from 1:1 to 1:90 (Weier et al. 1993). Generally the proportion of N_2O tends to increase when soil oxygen supply is adequate and there is both soluble C and N available, for example, after manure spreading (Dittert et al. 2005).

Some estimates of the total amount of denitrified N have been given for different types of grazed pastures and the values range from 154 kg N ha^{-1} y^{-1} on a clay loam soil receiving 500 kg N ha^{-1} y^{-1} to 5 kg N $ha^{-1}y^{-1}$ on an unfertilized silt loam soil (Watson et al. 1992; Ledgard et al. 1999). In the present study the soil was a well drained fine sand which puts it into the category of medium denitrification potential (D'Haene et al. 2003). The oxygen supply in light sandy soil should have been adequate most of the time, which suggests a higher proportion of N_2O as the end products of denitrification. The grass pasture was fertilized with reasonable amount of ammonium nitrate (50:50), and this also enhances the N_2O compared to N_2 emissions. As the measured N_2O emission was quite low, it seems likely that the total amount of denitrified N was at the lower end of the presented scale.

3.4.5 Leaching and surface runoff

There was great variation between the lysimeters in both EXP II and EXP III in the N concentration and the amount of infiltrated water. The variation is probably caused by the impacts of regular ploughing and reseeding on the porosity and structure of the soil. Later on, when the surface soil is compacted, the porosity is stabilized and macropores are decreased. However, the variation seems to be a natural effect too as the infiltration rate depended greatly on the soil texture, which differed between the lysimeters.

In EXP II during the grass cover years (1998-1999) with 220 kg fertilizer N ha^{-1} for both cut and grazed treatments the NO_3 -N concentrations remained low (< 5 mg NO_3-N l^{-1}), the total amount of N leached from both areas was low and the treatments did not differ from each other.

The amount of leached total N expressed as a percentage of the applied fertilizer N was very low (0.63 % and 0.5 % in 1998 and 1999, respectively) compared with many other studies. For example, the amount of leached N was 17.5 - 19.2 % of the fertilizer N according to Benke (1992), Scholefield et al. (1993) and McDuff et al. (1990). Those studies were performed in regions where precipitation clearly exceeded evaporation. More comparable figures were given by Barraclough et al. (1992), 2.6 - 4.9 %. Their study was conducted in Hurley, UK, where the precipitation (694 mm) and calculated drainage (167–177 mm) were almost the same as in this study.

Another reason for the small quantities of leached N is that the sward was only 4 years old. Watson and Foy (2001) suggested that in Northern Ireland, N retention for swards less than 10 years old was about 80 kg N ha^{-1} year^{-1}. Therefore, immobilisation was probably an important factor causing reduced N leaching in this case as well. Other possible explanations for low leaching figures are a short grazing season and the fact that this was the first time the site had been used for pasture.

Differing from EXP II, there was a clear cumulative effect in N leaching in EXP III, both in the N-fertilized grass and the grass-clover (Fig 8.). The obvious reason for this was that the N inputs were considerably larger than the N outputs per year in both treatments. Another possible reason for this is the ley farming system with 3-4-year rotations. The positive N balance on pasture causes N accumulation in the soil during the first years after renewal and increases the N leaching later. It is also likely that there was a residual effect of EXP II. Cumulation effects have been found also in other short-term (3 years) experiments (Sprosen et al. 1997; Monaghan et al. 2005). In contrast, (Tyson et al. 1997) found no cumulative effect on permanent grassland and neither did Ledgard et al. (1999) in a 3-year experiment.

In Exp III both the N concentration in the leachate and the amount of leached N increased during the course of the experiment in both treatments.

In EXP III more total N leached from both the fertilized grass pasture and unfertilized grass-clover pasture to begin with compared to the preceeding EXP II. However, the influence of the EXP II on the results of EXP III was negligible, as in the beginning of the EXP III the N concentration of the leachate was

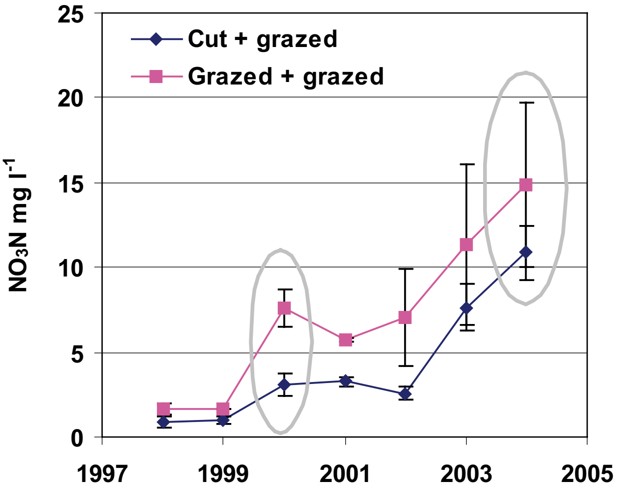

Figure 8. Cumulative effect of repeated grazing in Exp II and III on leachate NO_3-N concentration compared to cutting followed by grazed lysimeters in Exp II and Exp III. Renewal years are circled.

below 5 mg l^{-1} and there was no difference between grass and grass-clover lysimeters. In EXP III, significantly more N leached from the fertilized grass pasture than from the grass-clover pasture when the whole ley rotation was taken into account.

The N concentration increased during the experimental years for both treatments. During the third grazing year, the average NO_3-N concentration of the leachate originating from the grass pasture exceeded the EU limit for drinking water of 11.3 mg N l^{-1}. The N concentration of the grass-clover pasture leachate remained below the EU limit throughout the experiment. The amounts of leached NH_4-N and organic N were small.

As the stocking rate of the treatments were close to each other, a probable reason for the lower NO_3-N leaching loss from the grass-clover pasture is the adaptation capability of the SNF in white clover. According to Vinther (1998) SNF can be decreased in the urine patches that are the main source of N leaching on pastures and the clover stolons utilize urine N instead, thus diminishing the amount of free mineral N in the soil. In contrast at the fertilized grass pasture, N in urine patches was poorly utilized by the grass since meadow fescue and timothy are slow to recover from defoliation (Virkajärvi 2004) and respond inefficiently to large amounts of N (Hall et al. 2003).

In EXP II during the grazing years the N load at the watering point was nearly double that for the rest of the pasture. This was directly reflected in the NO_3-N concentration that was more than twice the EU limit and in the amount of leached total N was 151 kg ha^{-1} per hectare after the renovation. The N leaching losses from the lysimeters with drinking water supply (DWS) in EXP III during grazing years increased from 20 to 105 kg N ha^{-1} in the grass pasture and from 16 to 43 kg N ha^{-1} in the grass-clover pasture. The amount of leached N after renewal was 142 and 66 kg N ha^{-1} from grass and grass-clover DWS treatments, respectively.

Due to different stocking rates on DWS in EXP III the leaching from the grass pasture lysimeter with DWS was 0.46 kg total N per grazing day calculated for the whole four-year period, and in the grass-clover pasture it was 0.42 kg total N per grazing day. This confirmed the result of EXP II. The area around the DWS suffered from treading that can be classified as severe, according to the pictures presented by Menneer et al. (2005). Thus, there was no vegetation to utilize the fertilizer and excretal N in the area. The cows tended to use the DWS site as a congregation area and this probably increased the amount of dung and urine deposited on the lysimeter. If used as drinking water, the NO_3-N concentration in the lysimeter water below the watering point after renewal was high enough to cause spontaneous abortion in cattle (eg. Yeruham et al. 1997) and possibly development disturbance in human babies (WHO 1978).

Renewal

During the renewal in EXP II after glyphosate treatment and ploughing, the total and NO_3-N concentrations rose significantly in the grazed treatment reaching the EU limit for drinking water compared with the cut treatment that remained low.

The main reason for the N leaching pattern was the glyphosate treatment in autumn 1999, which released the N bound in the vegetation. Mineralizing N was then vulnerable to leaching in the following spring. The estimated amount of N in the vegetation (not measured) before the glyphosate treatment was 45 – 60 kg ha^{-1}. Moreover, the N mineralized from the organic pool of soil and cattle excreta was no longer taken up by the grass cover. The effect of glyphosate on soil microbes is minor (Heinonen-Tanski et al. 1985) and microbes probably did not have a significant effect on N leaching (Malkomes 1988).

Altogether, in EXP III there was at least 200 and 195 kg mineral or easily mineralizable N ha^{-1} in the grass and in grass-clover treatments, respectively, remaining in the above-ground vegetation, roots and soil mineral N (0-25 cm) in autumn 2003, prior to the renewal of the sward in the following spring. In addition, there was also a substantial (but unknown) amount of dung N remaining on the soil surface after three grazing years on both treatments. This effect was shown in N leaching during the renewal year, when the NO_3-N concentration of the grazed grass treatment was considerably higher than in EXP II. Also the organic N concentration of the leachate increased, but there was still no difference between the treatments. In EXP III the large amount of leachate in the renewal year can be attributed to the high precipitation during that year and to the effect of ploughing.

When the amount of leached N for the whole ley rotation in EXP III is related to the N yield in milk and HM, we get the proportions of 0.32 and 0.20 kg leached N per kg produced N for the grass pasture and the grass-clover pasture, respectively. N leaching from grass-clover during the entire ley rotation was 60 % of the leaching from the fertilized grass pasture. This is in agreement with the conclusions of Cuttle et al. (1998) and Ledgard et al. (1999), who stated that the amount – not the form – of N input is the most important factor affecting N leaching losses. Based on this, short-term grass-clover pastures can be considered environmentally beneficial when compared to intensively fertilized grass pastures under similar conditions to those in this study.

Unexpectedly, the timing of sward destruction did not affect leaching. In EXP II sward destruction took place in autumn 1999 and in EXP III in spring 2004, but in both experiments the N leaching during the following winter and spring was high and comparable. A possible reason for the high N leaching loss after spring renewal was that the catch crop (annual ryegrass) was grazed in late autumn, which increased N leaching during the following winter and spring (Wachendorf et al. 2008).

Surface runoff

Surface runoff in light textured mineral soils occurs mainly in spring when soil frost prevents most of the water infiltrating through the soil. The amount of surface runoff in EXP III was rather similar throughout the grazing years, being approximately 39 % of the total amount of water leached and 15 % of the average precipitation. After ploughing and renewal of the sward, the surface runoff was decreased significantly. The total N concentration in the surface runoff from the grass pasture was below 7 mg l^{-1} throughout the experiment. Over 60 % of the total N in surface runoff was in the form of ammonium N. The total amount of N lost in this way increased over the grazing years but was cut by half during the renewal year. The concentrations and the amounts of NO_3-N and organic N in runoff were low during the experimental years.

The quantity of N lost in the surface runoff remained below 5 kg N ha^{-1} y^{-1}. As the eutrophication of Finnish inland surface waters is mostly limited by phosphorus (Rekolainen 1989), the importance of such low amounts of N in the surface runoff is small. During the renewal year the amount of N in surface runoff was even less, because the surface runoff as a proportion of the total water flow was strongly reduced and the concentration of N in surface runoff was also lower due to ploughing.

3.5 N balance

To fully understand the N flows and losses in grassland and to compare different management alternatives, a detailed N balance is a valuable tool. Balance scale can vary from micro plot to whole catchment area, but most commonly balances are calculated for individual fields. This was also the starting point in these experiments. However, the field balance may be misleading when the whole farm is considered, as the N balances are different for differently managed fields. The balances represented below are combined from experiments II-IV and from the N_2O emission data of Virkajärvi et al. (unpublished). Detailed descriptions of different N inputs and outputs are in sections above.

As Ryden (1984) states, it is extremely difficult to obtain accurate measurements for all the inputs and outputs of N that occur in grassland during a year, and the difficulty is greater for outputs than the inputs. For the pasture and whole ley rotation in severe winter conditions it is even more difficult. In intensively managed 3 to 4 year ley rotations N immobilization/mineralization turnover rate is rapid.

In EXP II the gross herbage production of plots cut for silage was 46 % and 13 % larger than the grazed plots in 1998 and 1999, respectively. Even though the result was expected, it is striking how large the difference in balance between the grazed and cut treatments in EXP II is (Table 9). The sward was already 2 years old when the experiment started, so the balance for the whole ley rotation could not be calculated, but for these three years including renewal, the total difference is 384 kg N ha^{-1} as the cut sward lost 225 kg N ha^{-1} and the grazed sward gained 159 kg N ha^{-1}. Negative N balance for artificially fertilized cut sward is quite a common result. Nevens and Rehuel (2003) measured 188, 100 and 29 kg N ha^{-1} y^{-1} negative balance between N fertilizer and N yield for 100, 200 and 400 kg N ha^{-1} y^{-1} fertilized cut swards, respectively. Apparent N recovery exceeding 100 % in fertilizer cut swards is also reported by Lantinga et al. (2001) and Eriksen-Hamel and Whalen (2008). In contrast, Salazar et al. (2005) measured 123-147 kg ha^{-1} y^{-1} N surplus using slurry or manure for cut ryegrass/clover sward, but in this case N amounts used were much higher than in EXP II and included N fixing white clover.

In EXP II the N cycle of the cut plots was incomplete because usually the cut plots renewal is done with slurry application, which increases the N input in cut swards to a maximum of 170 kg N ha^{-1} y^{-1} (maximum amount of organic manure N allowed in nitrate vulnerable zones, EU Nitrate Directive) for the whole ley rotation. In EXP II this was not possible due to technical reasons. The balance for the grazed sward in EXP II was highly positive due to low grass growth, that led to low numbers of cows as the HA was fixed to 23 kg pasture DM for each cow per day.

It must be taken into account that surface runoff, NH_3 volatilization, denitrification and foetal growth were not measured or estimated in EXP II but should be included in the balance. Therefore the balance in this case does not represent the amount of immobilized N in the soil.

Table 9. N Balance of cut and grazed area in Exp II.

Nitrogen inputs kg ha^{-1} y^{-1}	1998		1999		Renewal	
	Cut	Grazed	Cut	Grazed	Cut	Grazed
Fertilizer	220	220	220	220	-	-
Concentrates		26		36		
Deposition[1]	2	2	2	2	2	2
Total input	222	249	222	258	2	2
Nitrogen outputs kg ha^{-1} y^{-1}						
N yield in grass dry matter[2]	233		245		90	90
Milk		26		49		
Excretion during milking		19		27		
Leaching	2	1	1	1	12	46
Total output	235	47	246	77	192	226
Balance kg ha^{-1} y^{-1}	-12	202	-23	181	-190	-224

(1 Vuorenmaa et al. 1998

(2 DM yield of renewal year was not measured separately for grazed and cut treatments.

As the balance for EXP II revealed the large difference in N surplus between cut and grazed sward, in EXP III the aim was to measure N cycling on differently managed grazed swards to see if large N surpluses could be decreased by using white clover instead of fertilizer N and at the same time maintain the productivity of the pasture at an acceptable level. The other aim was to include all the N inputs and outputs to clarify the N cycling details. The results are represented in Table 10.

In contrast to the EXP II, the sward productivity in EXP III was high. As the cows used in the study were in the earlier state in lactation which enhances milk production capacity, the HA was also increased to 25 kg DM cow^{-1} d^{-1} and the amount of concentrates to 6 kg cow^{-1} d^{-1}. Due to higher productivity, more N was excreted in milk than in EXP II. Usually, the primary productivity of mixed swards is 0.70–0.80 of that of pure grass swards with high N-fertilizer (Andrews et al. 2007). In EXP III, the productivity of the grass-clover mixture was exceptionally high, as gross HM production of grass-clover was 8 % and milk N yield only 4 % lower than from the fertilized grass pasture.

The herbage N yields during the renewal year were high and equal for the grass and grass-clover pasture plots. Thus, we confirmed the results of Eriksen et al. (2004), who suggested that in the first year the residual nutrient effect of 3-year-old grazed grassland is sufficient and additional N fertilization is unnecessary. In agreement with our results, they did not find that grassland history – grass or grass-clover – had any influence on the residual effect (Eriksen et al. 2004).

Table 10. N Balance of the grass and grass-clover pastures in Exp III.

Nitrogen inputs kg ha^{-1} y^{-1}	Grazing years		Renewal	
	Grass	Clover	Grass	Clover
Fertilizer	220	0	0	0
Concentrates	67	62	15	15
Deposition(1	3	3	4	4
SNF(2	0	216	0	0
Total input	290	281	19	19
Nitrogen outputs kg ha^{-1} y^{-1}				
N yield in grass dry matter	0	0	144	143
Milk	69	66	20	20
Excretion during milking	71	66	19	19
Retention in pregnancy (3	4	4	1	1
Ammonia volatilization (EXP IV)(4	16	16	Nd	Nd
N_2O emission(5	3	5	Nd	Nd
Surface runoff(4	4	4	3	3
Leaching	17	9	60	40
Total output	184	170	247	226
Balance kg ha^{-1} y^{-1}	106	111	-228	-207

(1 Vuorenmaa et al. 2001 (2 Symbiotic N fixation based on Høgh-Jensen et al. (2004)(3 Estimated based on the N retention in uterus, placenta and foetus in cows that calve between the beginning of August and the end of October (see chapter 3.4.2) (4 Not determined for clover pasture, but assumed to be equal to grass pasture, Nd = Not determined (5 Virkajärvi (unpublished)

3.6 NCYCLE model

3.6.1 Background for modelling study

There is a wide range of results from pasture and cut grass N cycling from this study and thus it was possible to test if an already existing N cycling model could be fitted to these circumstances. There are numerous different N cycling models available (Cannavo et al. 2008). Choosing criteria for the model were that it should be developed for pasture and cut grass systems, it should include adjustable soil, water and animal parameters and it should be fairly simple to operate. One important criterion was that the model could be adjusted to new climatic circumstances. Based on these demands, the NCYCLE model (Scholefield et al. 1991) was chosen.

NCYCLE was developed for estimating N leaching losses and denitrification on cut grass and pastures in UK. Later, it has been updated and developed for different purposes to estimate N cycling on varying grasslands (Jarvis 1993; Worthington and Danks 1994; Rodda et al. 1995; Scholefield et al. 1996; Lord and Anthony 2000; Brown et al. 2005). The latest version of the NYCLE model was developed to estimate N cycling on Irish pastures (del Prado et al. 2006).

The purpose of using NCYCLE for the present study was to find out how close the figures calculated by the model were compared to the measured results. As NCYCLE is developed for UK climatic and soil types, it was expected that the results would not agree with this study. The other objective was to identify the main shortcomings of this model and how it could be devloped for Finnish conditions.

3.6.2 Description of NCYCLE model

NCYCLE is an empirical, deterministic and mass balance model, which calculates average annual fluxes of N per hectare within a beef or dairy grazing system and cutting only system. The input parameters are soil texture, drainage status, land use history, age of sward, climatic zone and atmospheric deposition zone. The output parameters are the N product and the amount of N that is leached, denitrified or volatilized per year (Fig 9.).

The main sub model of NCYCLE is the linear regression model that calculates the partition of the annual flux of soil inorganic N between ‘plant N’ and the ‘surplus N’ that is available for leaching and denitrification. The other sub model calculates the N ingested by the animal to milk and excreta, which is returned to the pasture. Inorganic N can be then lost via volatilization (from urine and dung), denitrification and leaching. Nitrogen loss by denitrification is based on soil texture and drainage status. Finally, the surplus N is accumulated in the soil leachable N pool. The detailed description of the model is given by Scholefield et al. (1991).

3.6.3 Results of the NCYCLE model compared to this study

The model was run using three years average N input and output values of grass pasture (Table 11). The grass-clover treatment was not included in this trial as this version of the model did not estimate N fixation by clover. The following input parameters were used in the model:

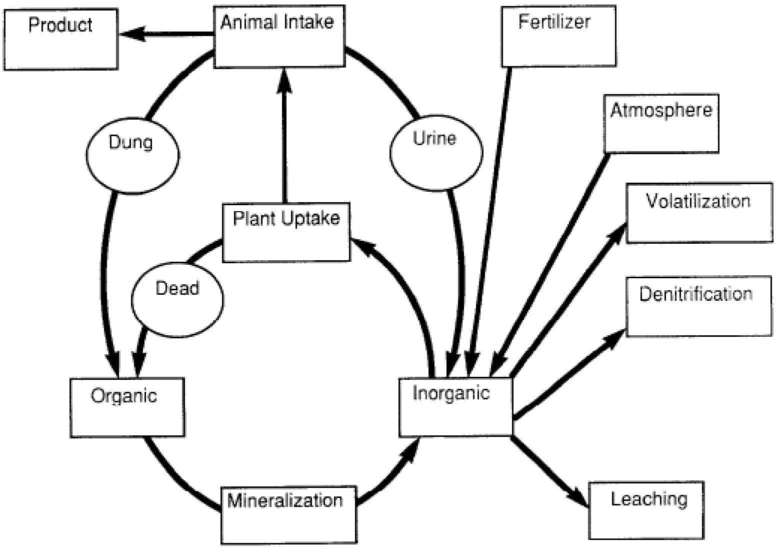

Figure 9. A flow diagram of the N transformations in grazed grassland within NCYCLE reprinted from Scholefield et al. (1991).

Dairy pasture system

Land use history: ley-arable rotation, (soil organic matter N mineralization starting value 75 kg inorganic N ha^{-1} y^{-1})

Soil texture: sandy loam

Age of sward: 2-3 years (soil organic matter N mineralization adjustment factor 0.9)

Drainage status: good (soil organic matter N mineralization adjustment factor 1.0)

Climatic zone: zone 3 (soil organic matter N mineralization adjustment factor 0.6)

Climatic zone 3 represents high latitude and altitude area in UK. This zone was the closest to the Finnish climatic conditions. However, the mean monthly temperatures and precipitation were higher than in Finland. The volume of leachate estimated by NCYCLE was 272 mm, when the measured value was only 141 mm.

Table 11. N cycling values measured in the study or calculated by the measured results compared to the estimates given by the NCYCLE model.

	NCYCLE Estimated value	Measured / calculated value
Fertilizer N kg N ha^{-1} y^{-1}	given	220
Atmospheric deposition kg N ha^{-1} y^{-1}	given	3
Plant uptake (shoots and roots) kg N ha^{-1} y^{-1}	376	nd
Plant N content %	3.37	3.07
HM utilization factor %	0.62	nd
Animal intake kg N ha^{-1} y^{-1}	233	219*
Net HM production kg DM ha^{-1} y^{-1}	6918	7117*
Product (milk production) kg N ha^{-1} y^{-1}	54	69
Dung kg N ha^{-1} y^{-1}	50	66*
Urine kg N ha^{-1} y^{-1}	130	123*
Dead plant material kg N ha^{-1} y^{-1}	143	nd
Mineralization kg N ha^{-1} y^{-1}	79	106
Net change in soil organic matter pool kg N ha^{-1} y^{-1}	113	110*
Soil inorganic N kg ha^{-1} y^{-1}	432	nd
h-factor (% of soil inorganic N flux kg ha^{-1} y^{-1} taken up by grass)	0.87	nd
v-factor (% urine N kg ha^{-1} y^{-1} volatilized as NH_3N)	given	0.13
NH_3N volatilization kg N ha^{-1} y^{-1}	18	16
Denitrification kg N ha^{-1} y^{-1}	5.7	nd
Leaching kg N ha^{-1} y^{-1}	32	17

* Value is calculated based on measured data.

The output parameters of the model are leaching, denitrification and volatilization. Leaching calculated by the model is 15 kg N ha^{-1} y^{-1} larger than the measured value of 17 kg N ha^{-1} y^{-1}. Denitrification was not measured in this study, but the N emitted as N_2O from the same experimental pasture was 4 kg ha^{-1} y^{-1} (Maljanen et al. 2007) and indicates that the denitrification figure given by the model is in general agreement. Ammonia volatilization estimated by NCYCLE and the measured value are almost equal.

The output parameters of NCYCLE are calculated from the soil inorganic N flux that is partitioned to plant N uptake and losses to the environment. The model's 'soil inorganic N flux' is a sum of fertilizer N and atmospheric deposition N which are user given values and urine N and N mineralized from soil organic matter which are estimated values.

The ‘soil inorganic N flux’ pool calculated by NCYCLE was 432 kg N ha^{-1} y^{-1} and the actual figure calculated using the same formulas from measured values was 452 kg N h^{-1} y^{-1}. As the calculated flux based on measured values is actually higher than the model predicts, the error in the leached N estimate must be caused either by too low an h-factor (the proportion of plant N uptake from soil inorganic N flux) or too high an estimate of soil N mineralization. The N yield of zero N fertilized plots was measured, so the error must be due to a high multiplier factor for decomposing root and stubble proportion (1.6) of herbage compared to UK. The net DM production, roots and stubble were not measured in the experiment, so it is difficult to estimate the actual plant N uptake and turnover.

The urine N amount in this study was calculated from the total N intake partition between milk, dung and urine based on the results from a physiological experiment (Sairanen et al. 2005) conducted with almost identical animals (live weight, milk production) and concentrate supply as used in this experiment. The calculated value of urine N deposition was only 7 kg ha^{-1} y^{-1} lower than the figure estimated by NCYCLE.

The proportion of plant N that cows consume (u-factor) is calculated for the sum of below ground and above ground N uptake. The u-factor suggested by the model is 0.62 (Ball and Field 1987 ref. Scholefield et al 1991). It seems high compared to DM utilization figures (60-79 %) obtained from Finnish experiments, where the utilization was calculated per pasture DM production cut to 5 cm stubble (Virkajärvi et al. 2002a) .

One factor that affects the u-factor and what NCYCLE does not take into account is the amount of concentrates fed to the cows during the grazing season. The amount of concentrates lowers the u-factor depending on the substitution rate of the concentrates. In this study the cows got 67 kg N ha^{-1} y^{-1} from concentrates and the estimated N intake from grass was 219 kg N ha^{-1} y^{-1} (Sairanen et al. 2005), which is 14 kg N ha^{-1} y^{-1} lower than the figure calculated by the model. As the u-factor suggested by NCYCLE is too high, more grass died and decomposed during the summer than was estimated by the model. However, the lack of concentrate N input in NCYCLE is compensated by the fact that, depending on the situation, cows spent approximately 25 % of the day in the milking parlour and the same proportion of the excretal N was deposited there, not returned to the pasture. In this study the amount left in the milking parlour was 71 kg N ha^{-1} y^{-1}, which is close to the amount of N given to the cows in concentrates.

Milk production of the cows in this study was 15 kg N ha^{-1} y^{-1} higher than calculated by the model. The model predicts that 23 % of the N intake is turned into product. In this study the actual number calculated from the estimated grass N intake (Sairanen et al. 2005), measured concentrate N intake and milk N yield was 24.3 % which is close to the value suggested by the model. The reason for higher milk N yield in this study was the concentrate supplementation.

Herbage N % estimate in NCYCLE was measured from cut grass in three weeks intervals, so it is quite high. It is used to calculate the N intake partition in product, urine and dung N. In this study, the measured N % of the grass was 3.07 % and as the cows were fed concentrates the N % of the whole diet was 2.93 %. As both the total DM intake and N utilization in milk production were higher than the model predicted, the estimated amount of N in urine and dung in this experiment were surprisingly close to the ones estimated by the model. Herbage DM yield in this study calculated from the estimated grass DM intake (Sairanen et al. 2005) and actual measured grass N % were also close to the values given by NCYCLE.

In the model, all N taken up by the plant and not transferred to the animal N intake pool and the proportion of N excreted in dung are added to the soil organic N pool. The amount of N mineralized from soil organic N pool is most difficult to estimate as the proportion of dead plant N depends on unknown gross herbage shoot and root production and the climatic variables that affect the mineralization rate. The starting value and soil organic matter N mineralization adjustment factors for age of the sward, drainage status and climatic zone are derived from studies conducted in UK and New Zealand (Scholefield et al. 1991). These adjustment factors should be recalculated from Finnish results to be able to give accurate N mineralization figures for this area. Thus, the fact that the amount of N not accounted for in the balance in this study (that is assumed to be immobilized in soil organic matter) is close to the value estimated by NCYCLE as net change in organic N, is probably coincidental.

In conclusion there are several difficulties in applying the unmodified NCYCLE model to the Finnish conditions. Despite this, NCYCLE could be developed for Finnish grasslands as there is all the required data available from Finnish experiments and furthermore, there is a ready protocol for adjusting the model (del Prado et al. 2006). The model requires the amount of N in concentrates and the amount of N excreted during milking time to be added to the input parameters as they affect the intensity of N cycling. Even more important, it requires locally valid grass growth rates (plant N uptake), changeable grass N content and the right adjustment factors for climate and soil to be able to calculate soil inorganic N flux, N mineralization rate, leaching and denitrification losses accurately.

Conclusions

1. Pasture N utilization is poor compared to silage cutting especially when high amounts of concentrates or protein supplementation is used.
2. N transformations and immobilisation/mineralization turnover are rapid due to short term ley conditions. When the management changes almost yearly, the soil N is in constant state of change and equilibrium is never achieved.
3. Winter conditions change the N dynamics in soil compared to areas where soil does not freeze. Microbial activity slows down, but still continues even in temperatures below zero. Freezing prevents most water movement in soil and NO_3-N is accumulated in soil. Nitrate discharges in spring through leaching and gaseous losses when soil thaws and snow cover (often containing over 130 mm water) melts.
4. White clover-grass mixtures decrease N leaching losses at pasture and result in more efficient N utilization compared to fertilized grass swards. Winter hardiness is an important factor in white clover persistence, so a winter hardy cultivar should be chosen.
5. Largest environmentally harmful N loss from pasture is N leaching. Most of N leaching occurs in spring. Other seasons of the year are usually not so important, unless the autumn is exceptionally wet. Nitrogen loss in surface runoff is small and not important.
6. Ammonia volatilization from urine and dung during dry weather is small. Rainfall decreases NH_3 emission even more. The importance of pastures as a source of NH_3 emission in Finland is minor and has been overestimated previously.
7. The watering facility area functions as a cattle congregation area and if the stocking rate is high, it receives a large amount of excretal N and suffers treading damage that destroys the vegetation and soil pore structure causing N leaching losses, surface runoff and gaseous emissions.
8. Sward renewal is the critical point of the N cycle in short term ley pastures. A vigorous mineralization pulse causes large N losses especially through leaching. Thus, N fertilization for newly sown sward and cover crops after pasture renewal is not needed.
9. Based on these results it is essential to include the whole ley rotation including renewal year in short-term ley studies because of the cumulative effect of N inputs in previous years and the N mineralization pulse after cultivation of the soil, which greatly increases N losses.

4 Practical implications

The aim of this section is to suggest possible measures for reducing the N load to the environment in the Nordic climate. It must be taken into account, that decreasing one source of N loss often increases another. Furthermore, to decrease N loss to the environment on intensively managed dairy farms mitigation measures must consider the N surplus of the whole farm. The measures that consider only sward management are not wholly effective (Cuttle et al. 2004).

Largest N losses in ley rotation occur during the sward renewal phase – especially in the first spring after ploughing – so mitigation measures should focus on trying to reduce the losses at this time. However, as mentioned earlier, the whole cycle of ley rotation affects the amount of N that is available for mineralization and losses after renewal.

4.1 Optimizing fertilizer use

As the major cause for the large N losses from the pasture is the poor utilization of N, the most efficient way to cut the losses is to reduce N fertilization. N fertilizer recommendations for pastures in Finland have been the same as for the silage swards (200-250 kg N ha^{-1}) which is quite high compared to the low N utilization of the grazed swards and the length of the growing season. Recommendations were lowered to 190 kg N ha^{-1} y^{-1} at the beginning of year 2006 based on the measurements and calculation in this study (EXP II and EXP III). The further lowering to 170 kg N ha^{-1} y^{-1} is planned on a new grazing study based on these experiments and performed on three fertilizer levels (MTT, unpublished) and it will take place in 2009.

Grass N concentration is affected by N fertilization rate, so reducing N fertilization according to the environmental demands lessens the N cycling via excreta. This decreases N losses by reducing the N concentration of urine and thus leaching and ammonia volatilization from urine patches (Peyrad and Astigarraga 1998).

4.2 Plant species and varieties

In Finland the pasture sward contains usually only grasses (timothy and meadow fescue) without legumes. If the cost of the N fertilizers continues to rise, it is likely that legume mixtures will receive more attention as alternatives to N fertilized swards.

In this study, unfertilized grass-clover pasture had only slightly lower productivity (4 % lower milk N yield than in grass pasture) but much better N utilization (40 % lower nitrogen leaching than in grass pasture) calculated per hectare for the whole ley rotation, than fertilized grass pasture. Therefore, favouring clover mixtures would also be an effective measure to restrict the N leaching where clover based swards could be used.

4.3 Stocking rate and supplementation

The amount of the excretal N returns to the pasture depends mostly on the stocking rate. Increasing stocking rate has several effects: 1) it may increase N utilization and N output in products 2) it increases N cycling via excreta and 3) may increase N input through protein rich concentrates.

The diet N concentration determines how the N surplus in grazing animals is divided between dung and urine. If the diet is high in N, more N will be excreted in urine than in dung. The higher the urine N concentration and amount, the more N will be lost by ammonia volatilization and leaching.

4.4 The location of water supply

N leaching from the area with a drinking water supply was 2-3 times greater than that from the other pasture area when calculated for the whole ley rotation. Relative stocking rates near a water supply are much larger compared to the rest of the pasture area as the cattle use it as a congregation area. Thus, it receives a large amount of excretal N and often suffers severe treading damage that destroys the vegetation. As a result, the area around the watering facility acts as a point source for N leaching from pasture. To avoid this adverse effect, the location of the watering facility should be changed periodically so that serious treading damage does not occur and excreta are more evenly distributed.

4.5 Length of the grazing season

Intensive grazing should be avoided in late autumn. Although this was not actually studied in these experiments there was a large leaching pulse after grazing of the annual ryegrass in late autumn after renewal. There is also solid evidence from the literature that autumn grazing increases N leaching losses, since grass can not utilize nitrogen efficiently in late autumn and thus more N is vulnerable for leaching during the winter (Wachendorf et al. 2008).

4.6 Measures for pasture renewal

On light mineral soils ploughing in the spring followed by an efficient catch crop such as barley undersown with annual ryegrass lessens the leaching losses compared to destroying the sward in the previous autumn. There is no need for N fertilization after renewal of at least two year old pasture, but the N accumulated in the soil provides an efficient amount of mineral N to establish a new sward with cover crop. Catch crop yield should be harvested by cutting rather than grazing, since late autumn grazing increases N leaching in the following spring.

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