Nitrogen distribution and potential nitrate leaching in a combined production system of energy crops and free range pigs

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Master of Science Thesis by

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Preface

With this master project my education in biology at Aarhus University comes to an end. The experimental work was carried out at Research Center Foulum, Aarhus University during the period March 2009 to April 2010, where my work started in late summer 2009. The project presented in this thesis is the preliminary work to a manuscript planned submitted to Agricultural Systems during 2011.

I would like to acknowledge the people who helped me in this project:

My supervisor, Uffe Jørgensen, has been a great help during the whole process from the planning of the investigation to the writing of the thesis. I want to thank him for his big interest in the project and for all help. I also wish to thank Hans Brix, Institute of Biological Science, Aarhus University, for being my internal supervisor and for all of his help during writing of the thesis.

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Contents

Abstract

There is a conflict between animal welfare and nitrogen pollution in free range pig production. In response to the concern about nitrogen being lost to the environment and the need of sources of renewable energy, a combined production system of free range pigs and perennial energy crops was established. The pigs caused an uneven distribution of mineral nitrogen in the soil verified by observations of defecation behavior and soil N_{min} analyses. The investigation was carried out from March 2009 to April 2010. Areas planted with energy crops were favoured by the pigs for excretion of faces and urine. This created nitrogen hot spots with risk of nitrogen leaching. Stocking density had a pronounced effect on nitrogen losses per ha. After 16 weeks with a high stocking density (372 kgN/ha) rates of nitrogen losses to the environment were estimated for nitrate leaching (30 kgN/ha), ammonia volatilization (37 kgN/ha) and denitrification (63 kgN/ha). In comparison reduced stocking density (116 kgN/ha) resulted in 69 % less nitrogen removed from the paddocks with the pigs, when they were sent to the abattoir. However, reduced stocking had generally a smaller influence on the environment from estimated nitrate leaching (4 kgN/ha), ammonia volatilization (12 kgN/ha) and denitrification (20 kgN/ha). Additionally around 70 % less nitrogen was left for accumulation in soil at the low stocking density. However, the investigated energy crops were resistant to the rooting behavior of the pigs and were estimated to have a crop nitrogen off-take, if harvested in summer, of 87 and 60 kgN/ha at high and low stocking densities respectively. These values are probably underestimated and further investigations are needed. Paddocks planted with energy crops are a better alternative to open grassland with less persistent crops and higher potentials of nitrogen leaching.

Resumé

I frilandsgriseproduktion er der i dag en konflikt imellem dyrevelfærd og kvælstofbelastning af miljøet. Som følge af dette og et behov for vedvarende energikilder blev et system, der kombinerer frilandsgriseproduktion og flerårige energiafgrøder etableret. En ujævn fordeling af mineralsk kvælstof i jorden blev påvist ved observation af grisenes afsætning af fæces og urin, samt ved N_{min} analyser af jorden. Undersøgelsen forløb fra marts 2009 til april 2010. Grisene havde præferencer for at afsætte urin og fæces i arealer plantet med energiafgrøder. Jorden i disse områder blev således kvælstofholdig og en risiko for kvælstofudvaskning opstod. Efter 16 uger med høj belægningsgrad (372 kgN/ha) blev der estimeret en kvælstofudledning til miljøet fra nitratudvaskning (30 kgN/ha), ammoniakfordampning (37 kgN/ha) og denitrifikation (63 kgN/ha). Ved reduceret belægningsgrad (116 kgN/ha) blev 69 % mindre kvælstof fjernet, fra foldsystemet, med grisene ved slagtning. Dog havde den reducerede belægningsgrad generelt en mindre indflydelse på tilførslen af kvælstof til miljøet i form af kvælstofudvaskning (4 kgN/ha), ammoniakfordampning (12 kgN/ha) og denitrifikation (20 kgN/ha). Derudover blev 70 % mindre kvælstof efterladt til akkumulering i jorden, ved lav belægningsgrad. Den mulige fjernelse af kvælstof med energiafgrøderne blev om sommeren estimeret til at være hhv. 87 kgN/ha og 60 kgN/ha ved høj og lav belægningsgrad. Disse værdier er muligvis underestimerede og yderligere undersøgelser er nødvendige. Folde plantet med energiafgrøder er et bedre alternativ til åbne græsarealer med mindre hårdføre planter og højere potentialer for kvælstofudvaskning.

1. Introduction

Organic pig production is in Denmark based on free range sow units (Økologisk Landsforening, 2007). Free range pig production benefits in terms of animal welfare and low costs of buildings and equipment (Deering and Shepherd, 1985). Unfortunately, the high throughput of nutrients during grazing creates a risk of environmental pollution (Murphy et al., 2000; Petersen et al., 2001; Sommer et al., 2001; Williams et al., 2000; Worthington and Danks, 1992). This is especially true for nitrogen (N). As a result of the behavior of pigs, feces and urine are not placed uniformly in a paddock. Hence, there is potentially a high concentration of N in relative small areas in a paddock creating 'hotspots' for nitrate (NO_3) leaching (Eriksen and Kristensen, 2001; Sommer et al., 2001; Williams et al., 2000). This issue is additionally complicated by the trampling and rooting habits of the pigs. Plant cover like grass is easily turned over resulting in an increased risk of NO_3 leaching to ground- and surface waters (Williams et al., 2000). High concentrations of N make groundwater and surface water unsuitable as drinking water. Enhanced emissions of N to surface waters may cause eutrophication, where an increase in productivity can change the biological communities and cause oxygen deficiency (Iversen et al., 1998). Since inputs of N are low on organic farms, compared with the supply on traditional farms, losses may reduce crop production (Sommer et al., 2001). In order to minimize these effects it is therefore important to reduce losses of N and maintain N in the agricultural system.

It has earlier been described that established perennial crops are able to decrease NO_3 leaching (Jorgensen, 2005). By establishing permanent energy crops like willow and miscanthus soil tillage is avoided and a deep root system is created. These energy crops are able to reduce annual NO_3 leaching with 40-65 kg N/ha on sandy soils if the land use is changed from conventional crops (Jorgensen, 2005). By comparison annual leaching from agriculture on sandy soils in Denmark is estimated to be more than 70kg N/ha (Jorgensen, 2005). From free range pig production high amounts of N leaching have been calculated (Eriksen et al., 2002) depending on stocking rate, feed intake and management. It is expected that areas planted with miscanthus or willow would hold a pool of ammonium (NH_4) and NO_3 that potentially could be leached from grassland, and also ensure uptake from deeper soil layers in spring. The effective root depth defined as the depth with a root density larger than 0.1 cm root/cm^3 (Miljøstyrelsen, 2001a) is for willow on loamy sand measured as 115-125 cm (Jorgensen and Schelde, 2001; Mortensen et al., 1998), while it for grass is less than 100cm

(Miljøstyrelsen, 2001b). About 70-90% of the grass roots are located in the upper 20cm of the soil (Bolinder et al., 2002).

According to the Danish Action Plan ‘Green Growth’, an additional reduction of 10.000 tons leached N from the agricultural areas is expected in 2015 (The Danish Government, 2009). It is therefore relevant to study whether the risk of NO_3 leaching can be reduced in free range pig productions if permanent energy crops as willow and miscanthus are planted in the paddocks. Another aim of the ‘Green Growth’ action plan is to enhance short rotation coppice in order to protect ground water quality and surface waters in intensively farmed areas. Short rotation coppice is one of the instruments to reduce green house gas emissions from agriculture (Klimakommissionen, 2010). Denmark is expected to grow 30.000 ha with perennial energy crops before 2020 according to the Danish national Action Plan for renewable energy (Klima- og Energiministeriet, 2010). Hence, it is relevant to investigate the possibilities of energy crop growth in outdoor animal husbandry.

The objective of this investigation is to examine how mineral N is distributed in the soil of a paddock in a combined production system of energy crops and free range pigs, and to estimate the potential NO_3 leaching from this system.

The concentrations of NO_3 and exchangeable NH_4 ions in the soil have been studied, at two different stocking densities and in different areas of vegetation in the paddocks.

2. Materials and methods

2.1 Site description and experimental design

The investigation was carried out in six established paddocks at Research Centre Foulum (56° 29´N, 9° 35´E). The site at Research Centre Foulum is a loamy sand soil according to USDA soil taxonomy (for further information see table app. 1). Each paddock was divided into different zones where each zone represented different types of crops or usage (Fig. 1). The experimental area was established in early May 1996. Two varieties of willow were planted in zones divided by areas planted with grass and miscanthus. Willow was planted in rows with a plant density of 1.1 plants pr m^2.The term w*illow* does here refer to the two clones Jorr and Bjørn. Jorr is a pure *Salix viminalis* while Bjørn refers to a cross breeding between *S. viminalis* and *S. schwerinii*. *Miscanthus* refers to the species *Miscanthus giganteus*, which is considered to be a hybrid between *M. sinensis* and *M. sacchariflorus* (Lindelaursen, 1993).

Rows of Jorr were planted in zone 2. Between the rows of Jorr different clones of poplar were planted (se app. 2). Rows of Jorr and Bjørn were established in zone 6.

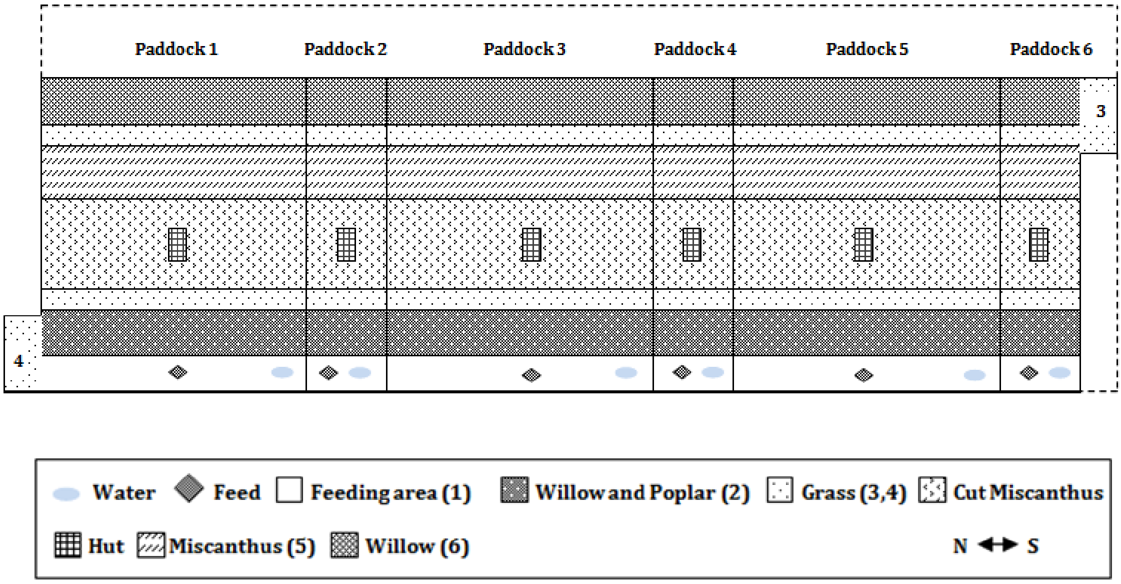


Figure 1 Plan illustrating the six free range pig paddocks. Each paddock is divided into zones with different types of vegetation or usage. The numbers in the legend refers to the zone numbers relevant in this study and the arrow illustrates, in which direction the paddocks are positioned. Paddock number 1 and number 6 are additionally expanded with 45 m^2 of grass (zone number 3 and 4). The areas framed by a broken line indicate the control areas planted with willow (area east of the paddocks) and grass (area south of the paddocks). Drawing is not to scale.

The rectangular paddocks were adjacent and of different size to obtain the two stocking densities (Table 1). The two outermost paddocks (nr. 1 and 6) were expanded with a zone of grass (45 m^2) added to each paddock in late August 2009. These grass zones had no previous history of free range pig production before the first sampling of mineral N (N_{min}) and thus the N_{min} concentration in the soil in this area could be used as a reference state before the introduction of pigs. N_{min} does here refer to the concentration of exchangeable NO_3 and NH_4 ions in the handled soil layer. The N_{min} concentration is calculated to kgN/ha in each soil layer. Furthermore a 2 m deep furrow was established between these grass zones and the zones planted with willow. This was done to cut off willow roots that had grown into the grass area, ensuring that roots would not affect the concentration of N_{min} in the soil. Apart from the two additional grass zones the paddocks had a previous history of free range pigs. In late March 2009 six fattener pigs were placed in each paddock for 8 weeks. Six of the vegetation zones in each of the six paddocks were selected for investigation (see fig. 1 for zone numbers) .The investigation also included two control areas planted with respectively grass (control area south of the paddocks) and the willow clone Bjørn (control area east of the paddocks). The control area planted with willow was established in 1996. Control areas are framed by broken lines in figure 1.

2.2 Animal management

In September 2009 six fattener pigs with a mean weight around 50 kg were inserted into each of the paddocks. The pigs were removed 8 weeks later when they had reached a mean weight around 100 kg. The round off stocking densities for the investigation periods: March – May 2009 and September – November 2009 is shown in table 1. An animal unit (AU) is a standardized measure of animals used for various agricultural purposes. One AU corresponds to 35 fattener pigs with a weight between 30-102 kg (Landbrugets Rådgivningscenter, 1993b). The experiment included two stocking densities; a high and a low. The high stocking density was estimated to cause a mean N deposition of 186 kg N/ha per paddock per measuring period. The low stocking density (mean of 58 kg N/ha per measuring period) was lower than the allowed N deposition of maximum 140 kg N/ha in accordance to Danish legislation (Landbrugets Rådgivningscenter, 1993a).

Table 1: Area, stocking densities and feed given in the two investigation periods

Measuring periods	Paddock number	Area of pasture (ha)	AU/ha	Feed (kgN/ha)
March - May 2009	1	0.22	0.6	110
March - May 2009	2	0.07	1.6	291
March - May 2009	3	0.22	0.6	109
March - May 2009	4	0.07	1.9	364
March - May 2009	5	0.22	0.6	106
March - May 2009	6	0.07	1.9	341
Sept. - Nov. 2009	1	0.22	0.6	131
Sept. - Nov. 2009	2	0.07	1.9	442
Sept. - Nov. 2009	3	0.22	0.6	134
Sept. - Nov. 2009	4	0.07	1.9	442
Sept. - Nov. 2009	5	0.22	0.6	134
Sept. - Nov. 2009	6	0.07	1.8	416

The stocking densities varied because the sizes of the paddocks differed and because two animals were put down because of disease in the measuring period March-May 2009. One pig was put down after a few days (paddock 2) and is not included in the calculation of the stocking density. In paddock 5 a pig was put down after 42 days. The average growth rate was 885 g per pig per day and the pig was included in the calculation for the 42 days it was alive. During the entire period, water and feed (see table 1 for feed-N input) were offered to the pigs in the feeding area (zone 1), and a hut was positioned within 25 m of this point.

2.3 Registration of defecation behavior

The defecation behavior (defined as defecation behavior) of the pigs was monitored in spring and autumn 2009. The fattener pigs were observed two days every week from insertion to slaughtering (see app. 3 for registration table). In the investigation period March-May 2009 behavioral observations of the pigs and the zone of occupation were registered from 08.00 am-01.30 pm one day a week and from 02.00 pm to 07.30 pm another day in the same week. From September-November 2009 the observations were made from 08.00 am–03.30 pm at day one and from 04.00 pm-07.30 pm at day two in the same week. Each observation period per paddock lasted for 15 minutes, with two-minute-intervals of registration. This provided a snapshot of the defecation behavior of the pigs. Defecation and urination were recorded for the whole two-minute period. In the autumn the registration distinguished between the behavior urination and defecation. The initial paddock for registration of behavior was determined by rolling a die and the following registrations were in a numerical order. Every session lasted for one and a half hour.

2.4 Analytical methods

2.4.1 Soil sampling

In order to investigate the environmental effect of the defecation behavior of the pigs, soil samples were sampled for N_{min} analysis. Soil samples were sampled in two depths (0-25cm and 25-75cm), with a 100cm N_{min} soil auger model EHJ (see app. 4), at three occasions: (1) in late August/early September 2009 before the introduction of the fattener pigs; (2) in November 2009 immediately after removal of the pigs; and (3) in early April 2010 when there was no longer frost. At occasion 1; 16 soil samples were taken in a grid and bulked at 16 points in each of the chosen zones. This was done to get an overall impression of the average soil concentration of N_{min} in the zones. 16 soil samples in a zone provided 2 bulked soil

samples, respectively from the depths of 0-25cm and 25-75cm. Grids were made on the basis of the size of the zones (see app. 5 for grid values). Control samples were sampled in the two control areas outside the paddocks in order to get a reference soil N_{min} concentration. The control area planted with willow was divided into four plots (see fig. 3). One of the plots was excluded from the investigation because of disease in the willow. The reference plots planted with willow had no previous history of pig production, but were supplied with mineral fertilizer. The plots were fertilized with 75 kgN/ha in 2007 and after harvest in early 2009, 240 kg N/ha were applied in mineral fertilizer on the 22th of April 2009. It was possible to determine the amount of NO_3 in the soil water of this particular reference area since porous ceramic suction cups were installed in this field (Djurhuus and Jacobsen, 1995).
Determination of NO_3 is described later in section *2.4.2*. Two ceramic suction cups were placed in each plot in a depth of 175 cm and samples of soil water were collected two times a month in periods of soil water percolation. When no water was present a value corresponding to half of the detection limit was used (0.05 mg/l).
In each of the willow plots, 8, 8 and 3 soil samples were sampled at depth 0-25 cm, 25-75 cm and 75-150 cm, respectively, and bulked for each depth. These soil samples provided an average soil N_{min} for each plot at three depths. In the willow zones of the paddocks (fig 1, zone 6) additional soil samples were sampled in each paddock from the 75-150 cm soil layer in order to compare N_{min} in the deep soil layers of willow. Three samples were sampled and bulked for each paddock in the soil layer 75-150 cm. The soil layer 0-75 cm was removed with a soil drill and a soil sampler collected the soil sample in the 75-150 cm soil layer (see app. 4). The same procedure was done at occasion 2 and 3.
Evidence of e.g. urine hot spots might be indistinguishable in bulked soil samples from an entire zone of a paddock. Variation in N_{min} contents can be quite high between 16 soil samples, but difficult to observe, when the 16 samples are bulked to one soil sample. In order to get more detailed information of the distribution and concentration of soil N_{min} in the topsoil (0-25 cm depth), 99 soil samples were collected from the small paddocks: 2, 4 and 6 at occasion 2. Four soil samples were collected in an area with a radius of 30 cm and bulked to provide one soil sample at each of the 99 points. GPS coordinates were measured (Leica Geosystems, 2001) in each of the 99 points to create a map in ArcGIS (ESRI, 2004) (Fig. 6). Soil samples were stored at -20°C until further processing.

2.4.2 Mineral nitrogen analysis

Soil samples were mixed and strained in a 4mm soil strainer. The concentration of ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) were analyzed spectrophotometrically in all of the bulked samples after extraction with 1M KCl (Klute Arnold, 1996). Portions of moist soil (ca. 10 g) were extracted with 40 ml 1M KCl for 30 minutes (centrifuged, 20 rpm) for N_{min} determination (mg/l). Funnel holders were set up with glass fiber filters and the supernatant was gravity filtered through the folded filters. NO_3-N and NH_4-N in the KCl extracts were determined colorimetrically on a Technicon Autoanalyser II. NH_4^+ extracted from soil was determined by measuring the intensity of the emerald green color that forms upon treatment of an aliquot of the extract with salicylate and hypochlorite at high pH (see app. 6 for reactions). NO_3^- extracted from soil was reduced to nitrite (NO_2^-) by passage through a column of copperized cadmium. NO_2^- was estimated colorimetrically after treatment with a diazotizing reagent (sulfanilamide in HCl solution) and a coupling reagent (N-(1-naphthyl)-ethylenediamine in HCl solution) to form an azo-chromophore. The intensity of the reddish purple color that develops is proportional to the concentration of NO_3^- in the soil extract, or to the concentration of NO_3^- plus NO_2^- if NO_2^- is present (see app. 6 for reactions). Approximately 10 g of soil from each soil sample was weighed, and soil moisture was determined after drying at 105 °C for 24 hours. The values were expressed as kg N per hectare by taking in account the actual soil water content and with the assumption that the weight of the soil is 1.40 g/cm^3 at 0-25cm depth and 1.46 g/cm^3 at 25-75cm depth and 1,52 g/cm^3 at 75-150 cm depth (Heidman, 1989). Differences in soil N_{min} concentrations between measuring periods were used to estimate N leaching from the investigated zones. Besides the energy crops corresponding to approximately 56 % of the area of each paddock (27 % willow and 29 % miscanthus) the feeding area accounts for 9 % of the area (leaving approximately 35 % of the area for cut miscanthus and grass).

2.4.3 Nitrogen balance

A N balance was calculated for each of the two pig systems (large and small paddocks). The general N balance was calculated as N inputs in feed and atmospheric deposition minus the outputs: N retention in the pigs and N in losses from ammonia (NH_3) volatilization, denitrification, crop N off-take and N leaching. N input in feed was a calculation based on the feed manufacturer's production report on the feed mixtures. N retention in pigs was based on the assumption that pigs kept on grass until slaughter with a weight over 40 kg accounts for

30 % of the feed N input (Eriksen et al., 2006a). The atmospheric deposition of N was estimated from the DEHM-model (Danish Eulerian Hemispheric Model) (Christensen, 1997) using values from 2008. Viborg was chosen as the municipal in the model. NH_3 volatilization was predicted using assumptions from NERI 2001 (Andersen et al., 2001), and denitrification was estimated by the empirical model SIMDEN-LER version 1.2 (Vinther and Hansen, 2004). Characteristics of the soil layers used in the SimDen model are shown in appendix 1. The potential losses of N caused by leaching were estimated by conducting a N_{min} analysis. The difference in soil N_{min} between autumn 2009 and spring 2010 was used to estimate the potential N leaching. By setting up a water balance of willow paddocks using the COUP model (Jorgensen and Schelde, 2001) it was possible to calculate the NO_3 leaching from the willow reference area from autumn 2009 to spring 2010. Between two days where soil water samples were collected, mean percolation for the two days was multiplied with the total days between the dates. This was multiplied by the mean NO_3 concentration of the soil water of the two days. The NO_3 leaching from these between-day-periods where added together from November 2009 to April 2010. The NO_3 leaching from the suction cubs was compared with the soil N_{min} reduction from November 2009 to April 2010 and used to create a rough estimate of the potential NO_3 leaching from the paddocks.
Plant samples of miscanthus were taken in August 2009. From each of the six zones planted with miscanthus, 2 m^2 of above ground plant material were harvested and weighed. The harvest never included border plants. Two straws from each zone were weighed, oven dried (80 ºC) for 24 hours and the concentration of N in the dry matter (DM) plant material was analyzed in a Leco CNS-1000. Before analysis, the samples were ground. Total N concentration was determined by destructing the samples in pure oxygen, and during further steps, leaving N_2 in a helium carrier to be measured by a thermal conductivity cell as described by Hansen (Hansen, 1989). Literature values of N concentrations in plant material from willow were used to estimate the crop N off-take at summer harvest (table 3). N supply, clone and season of harvest were factors used to evaluate whether a reference could be used to estimate the N concentration in willow plant material. A willow evaporation bed in Gesten was used to estimate the N concentration in the willow from the small paddocks (Jorgensen, 2010). The plant density at Gesten was 1.6 plants pr m^2. Results from Gesten showed that 40% of the total N in plant material from Jorr harvested in September derived from leave material and was used to estimate the N concentration in September harvested willow. Results

from Mortensen et al (1998) was used to estimate the N concentration of willow in the large paddocks plus a 40 % increase since Mortensen et al. (1998) only included winter harvest (no leave material). Because of few planted poplars it was assumed that there was no difference in crop N off-take between willow and poplar. Crop N off-takes in table 3 are based on an assumption that 29% and 27% of the area in the paddocks were planted with miscanthus and willow, respectively.

2.4.4 Estimation of the water balance in willow

Percolation in the investigation period was calculated using the model COUP (version 3.0). The one-dimensional COUP-model (Lewan, 1993) was used for simulating the water use of the willow clone Bjørn and calculate the water balance of the soil. However, the model requires site specific information particularly on soul hydraulic parameters, which is not always available. The COUP model is based on two coupled differential equations describing water and heat flows in a one-dimensional soil profile. The model requires daily meteorological data and parameter values for soil and plant properties (soil water retention, hydraulic conductivity functions, root depth and leaf area development) as input (Jansson, 1998). Measurements on canopy development were not available for the clone Bjørn in the measuring period. However, earlier investigations were carried out at the same locality in 1998 and 1999 on willow clones (clone 183 and 112), via remote sensing monitoring (RVI). These data was manipulated, because the growth period of the willow clone Bjørn is longer because of its resistance to the fungus 'blight'. Development of canopy height was estimated based on time of harvest and harvested stems. Soil water content in the willow plots was measured using Time Domain Reflectometry (TDR) technique (Topp et al., 1980).
Soil hydraulic properties were estimated from soil texture analyzed in the experimental area (Jacobsen, 1989). Root depth was estimated from Mortensen et al. (1998) and meteorological data for driving the water balance model were supplied from the Foulum climate station. The calculations in the simulated water balance is started in 2007 and simulated to the end of August 2010. Percolation is simulated using soil water contents in the depths 0-20 cm, 0-50 cm, 0-100 cm and 0-150 cm.

2.4.5 SimDen - Estimation of denitrification

SimDen calculate denitrification on the basis of on the equation:

$$\text{Denitrification} = N_2O \text{ emission x } N_2/N_2O\text{-ratio}$$

If it is possible to estimate the dimension of the N_2O-emission and if the ratio between produced N_2 and N_2O is known, then is it possible to calculate the overall denitrification (N_2O+ N_2) as a multiple of the N_2O-emission and the N_2/N_2O-ratio (Vinther and Hansen, 2004). The N_2O-emission is calculated on the basis of N input and emission factors, while N_2/N_2O-ratios are set based on values from the literature. The dependency on soil type and manure application is in the model described as a function of the content of water in the soil and the availability of organic material. Denitrification encompasses microbiological processes by heterotrophic organisms' and is therefore affected by the availability of organic material, soil water content, the amount of oxygen in the soil and also the pH of the soil. The amount of N deposited in the paddocks was estimated from the input of feed-N. 70 % of the feed-N input is deposited in the field as urine and feces (Eriksen et al., 2006a) and 7% of this, accounts for NH_3 volatilization (Andersen et al., 2001).

2.5 Climatic conditions

Meteorological data were supplied from the Foulum climate station. The investigation was carried out in a period with low precipitation and a long winter period with temperatures under 0 ºC compared to the 30 year mean (Fig. 2).

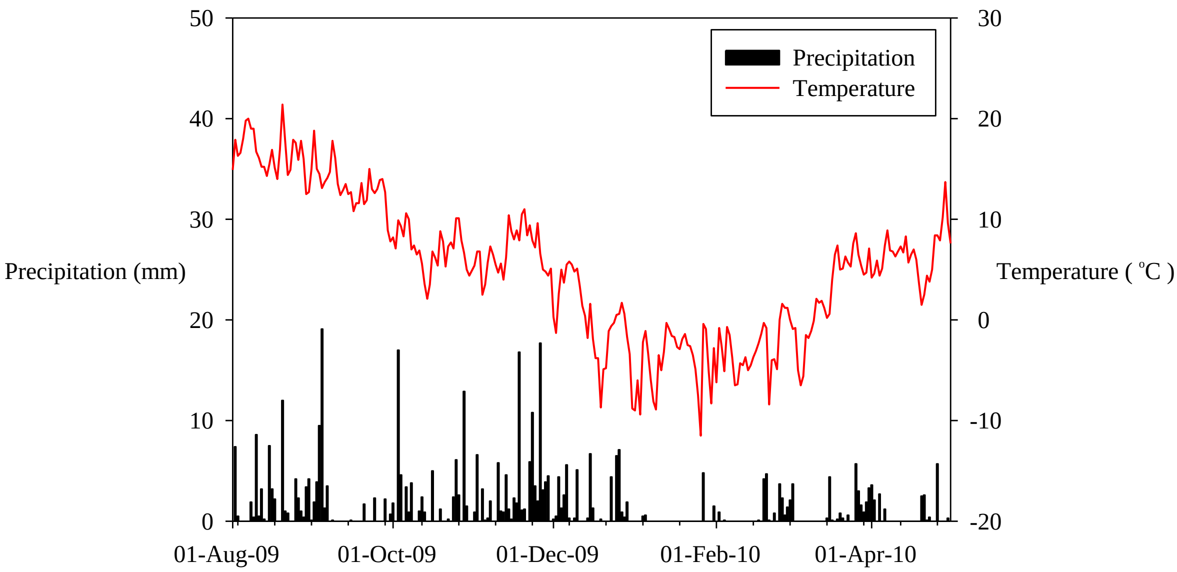


Figure 2 Diagram illustrating daily precipitation and day temperature from August 1, 2009 to April 30, 2010 at Research Center Foulum

Total precipitation during the soil sampling period was 395 mm, which is lower than the 30 year mean for the same period (550 mm) (The Danish Meteorological Institute, 2010). The average temperature at the site was in this period 5.08 °C, while the 30 year mean for the same period is 8.97 °C. Precipitation registration August 20, 2009 failed and the value is set to 12 mm according to measurements from the Danish Meteorological Institute for the central region of Jutland.

2.6 Statistical analysis

2.6.1 Defecation behavior of the pigs

The data was not normal distributed and hence a χ^2 test ($P<0.05$) was performed in order to estimate whether the observed defecation behavior differed from the expected defecation behavior. In this case the expected would be a uniform distribution of feces and urine across the area of the paddocks. Therefore the expected observations are handled in relation to the different areas of the zones. The number of observed defecations is represented as a percentage of the zone area. Zone areas, in which less than 5 observations were recorded, were taken out of the test.

2.6.2 Average mineral nitrogen of the soil in the different zones

The six paddocks were divided in three blocks, where each block represented a small and a large paddock. A two way analysis of variance (general linear model (GLM) procedure of SAS) (SAS Institute Inc, 2001) was carried out to investigate how the treatments ‘paddock size’ and ‘zone’ affected the concentration of N_{min} in the soil in each measuring period. Furthermore it was investigated whether there was an interaction between ‘paddock size’ and ‘zone’. This was done in each of the three soil layers: 0-25cm, 25-75cm and 0-75cm. Table 2 outlines the significant levels in the analysis. Data was log-transformed in order to obtain variance homogeneity.

2.6.3 Mineral nitrogen in the topsoil of the small paddocks in November 2009

The small paddocks were divided in zone blocks as illustrated in figure 6, and an average N_{min} content is calculated from each zone in each paddock. An analysis of variance (GLM procedure of SAS) (SAS Institute Inc, 2001) was carried out to see if the average N_{min} concentration in the soil differed significantly between zones.

2.6.4 Comparison of mineral nitrogen in the soil of different willow zones

The willow zones (Fig. 1, zone 6) were divided in 3 blocks where each block contained a willow zone from a small and a large paddock, but also a reference plot adjacent to the two paddocks (Fig 3).

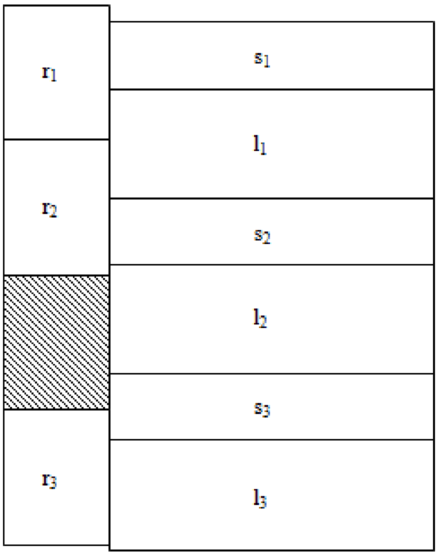


Figure 3 Paddocks divided in three blocks (numbers). Letters correspond to reference plots (r), small paddocks (s) and large paddocks (l). The shaded area illustrates the reference plot not included in the analysis because of disease in the willow. The drawing is not to scale.

An two way analysis of variance, mixed model procedure (MIXED) was carried out in SAS (SAS Institute Inc, 2001) to make a comparison of the soil N_{min} between the willow zones of the small and large paddocks, but also the reference plots planted with the willow clone Bjørn. A comparison of the mean N_{min} was done in three soil layers: 0-25cm, 25-75cm and 75-150cm. The difference between mean N_{min} in s, l and r was analyzed, at each soil depth and in each measuring period.

3. Results

3.1 Defecation behavior of the pigs

Figure 4 shows the distribution of the defecation behavior in the small and large paddocks in spring and autumn 2009, respectively. The defecation behavior was mainly performed in the zones planted with willow and poplar.

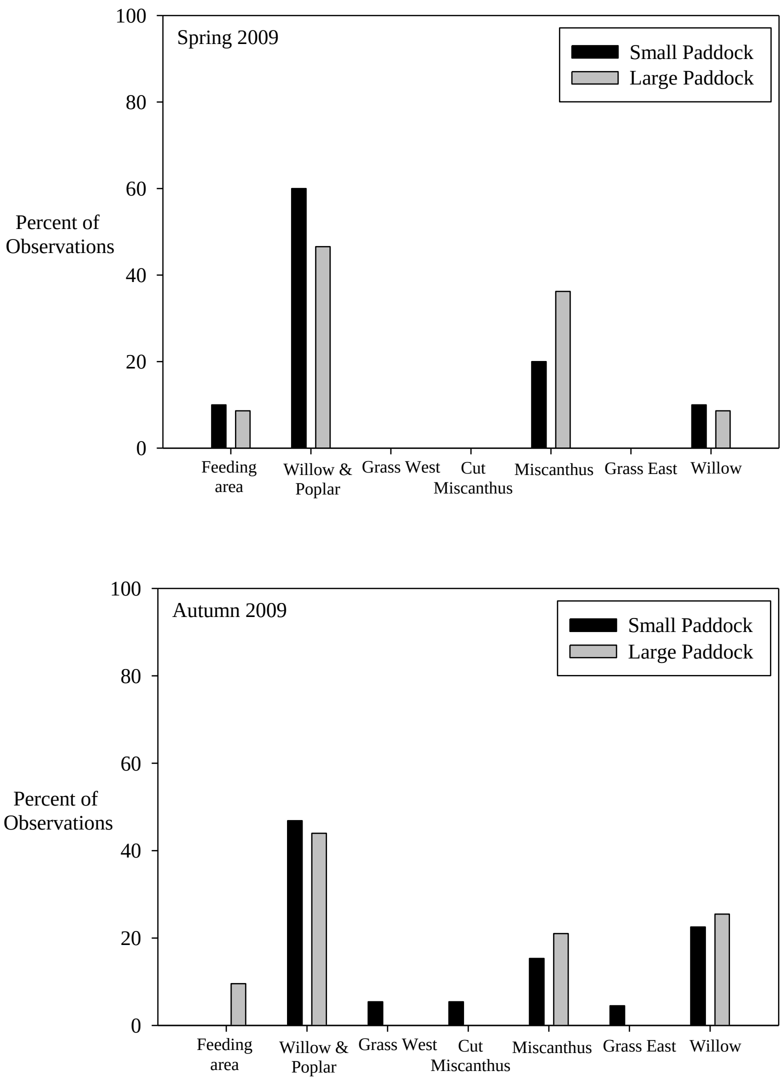


Figure 4 Distribution of defecation behavior in sub-zones of paddocks in spring (left) and autumn (right) 2009. Observations are shown for small (SP) and large (LP) paddocks. The observations are presented as percentage of observations registered in the different zone areas.

The distribution of defecation behavior was significantly different compared to a uniform distribution of defecation behavior in the zones. This was not only observed in the small (χ^2 = 80.7 ,df=3,P<0.0001) and large paddocks (χ^2 =34.7 ,df=3,P<0.0001) in spring, but also in the small (χ^2 =90.4 ,df=5,P<0.0001) and large paddocks (χ^2 =36.1 ,df=3,P<0.0001) of autumn 2009.

In both spring and autumn there were significantly more defecation in the zones planted with willow and poplar compared to the other zones (SP spring: χ^2 =80.7 ,df=1,P<0.0001, LP spring: χ^2 =32.7 ,df=1,P<0.0001 ,SP autumn: χ^2 =72.1 ,df=1,P<0.0001 and LP autumn: χ^2 =26 ,df=1,P<0.0001).

To sum up, pigs in the investigation did not distribute urine and feces uniformly, and significantly more defecation behavior was observed in the willow and poplar zones.

3.2 Distribution of mineral nitrogen

3.2.1 Average mineral nitrogen of the soil in the different zones

The analysis of variance showed that the N_{min} concentrations in the bulked soil samples were significantly different in the small and large paddocks. This is true for all three measuring periods and in all of the soil layers; 0-25cm, 25-75cm and 0-75cm (see outlines of the significance levels in table 2).

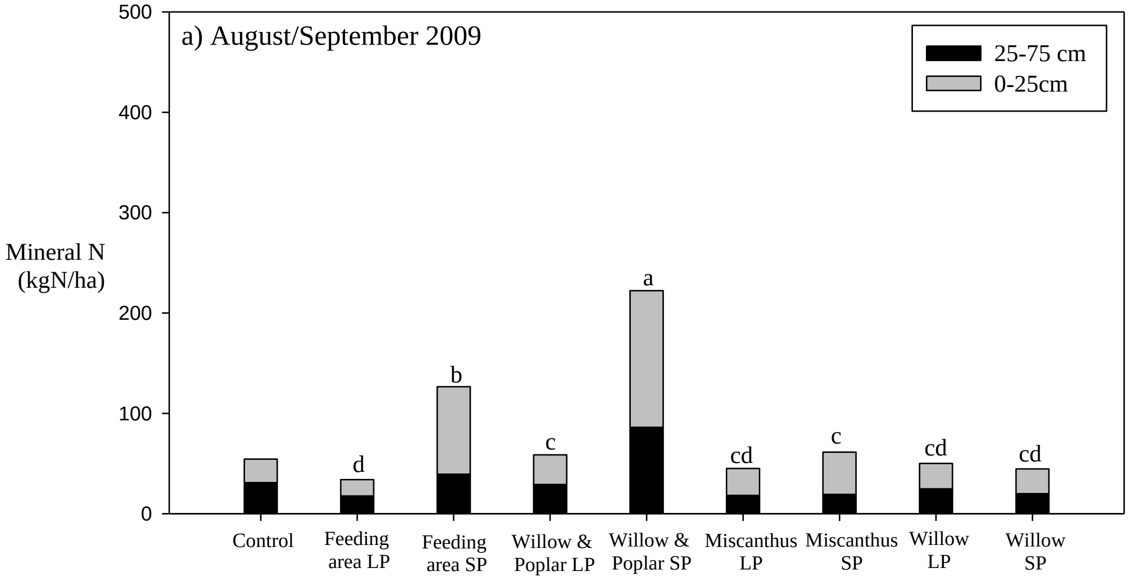
Table 2 Results of analysis of variance (significant levels) showing the effects of the main factors 'paddock size', 'zone' and their interaction on the N_{min} contents in 3 soil depths

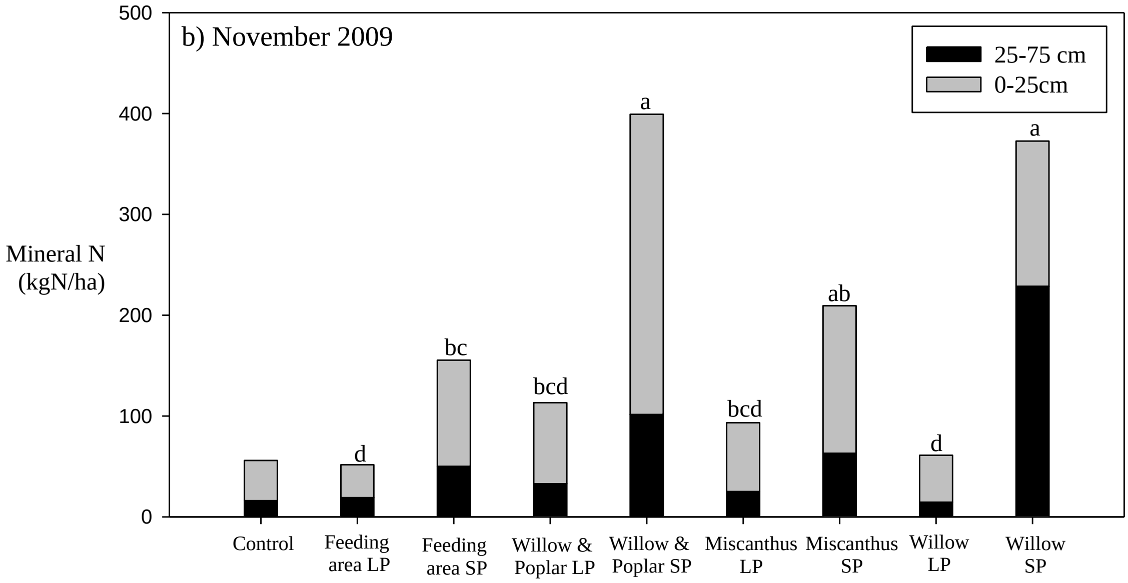
Soil depth	Measuring Period	Size of paddock	Difference between zones	Interaction between paddock size and zones
0-25cm	Aug./Sept	***	***	***
	Nov.	***	*	NS
	April	***	NS	NS
25-75cm	Aug./Sept	**	**	NS
	Nov.	***	NS	NS
	April	**	*	NS
0-75cm	Aug./Sept	***	***	**
	Nov.	***	*	NS
	April	***	NS	NS

* (P<0.05), ** (P<0.01), *** (P<0.001), NS (Not Significant)

In the measuring period August/September, the N_{min} distribution in the different zones depended on paddocks size, as shown by the significant interaction term of the analysis of variance.

In late August and early September 2009 (Fig. 3a), before the pigs were introduced to the paddocks 57 % of the total measured N_{min} was on average NH_4-N.





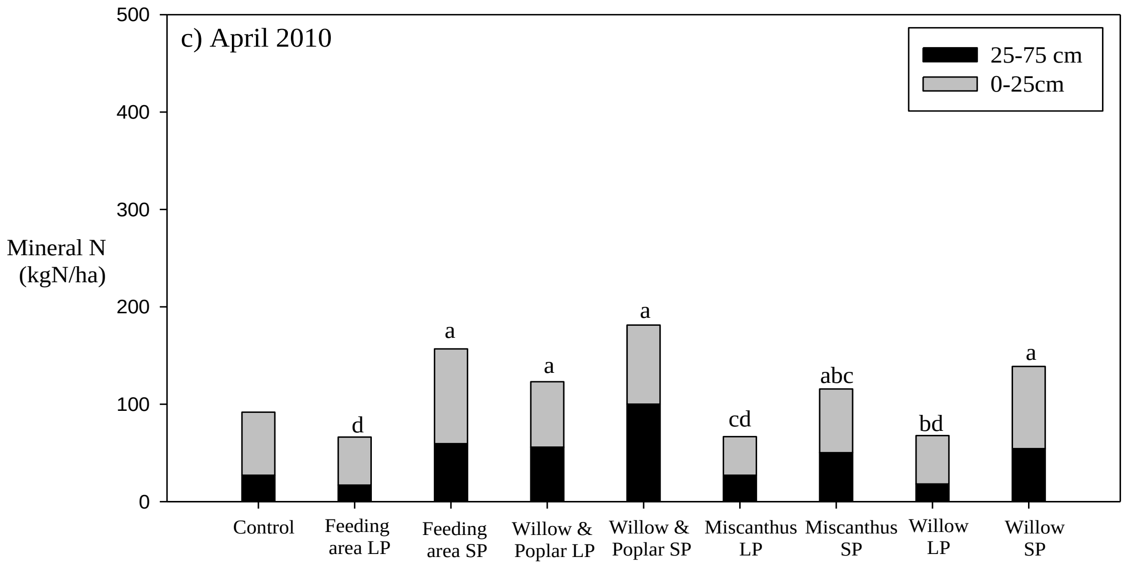


Figure 5 Average content of N_{min} (kg N/ha) in each of the investigated zones in each measuring period; a) August/September 2009, b) November 2009 and c) April 2010. The grey columns represent the content of N_{min} in the soil layer 0-25cm, while the black columns represent the content of N_{min} in the 25-75cm soil layer. The abbreviations SP and LP indicate the small and large paddocks, respectively. Identical letters above columns indicate that the content of N_{min} does not differ significantly between the relevant zones in the soil depth 0-75cm ($P<0.05$). The control plots were unreplicated and included as a reference.

The average N_{min} content was significantly higher in the zone planted with willow and poplar compared to the other zones in the small paddocks (Fig. 5a) and was true for both soil layers. Except for the willow and poplar-zones in the small paddocks, the average soil content of N_{min} was significantly higher in the feeding areas in the small paddocks compared to the other zones in the 0-75cm soil layer.

In November 2009, after 8 weeks with fattening pigs in the paddocks, the N_{min} level had increased considerable. NH_4-N levels were especially high. On average 74% of the N_{min} was in the form of NH_4, but this varied from 21 to 98%. The highest mean N_{min} content was measured in the willow and poplar zones of the small paddocks. Concerning the small paddocks, no significant difference was found between zones planted with energy crops in the 0-75 cm soil layer. The mean N_{min} contents of the willow and poplar zones and the willow zones were significantly higher than the N_{min} of the feeding area. The N_{min} contents of the large paddocks also increased from August/September to November, especially the content in the 0-25cm soil layer.

In April 2010 the total N_{min} concentration of the soil consisted of 63% NH_4-N. In the small paddocks, no significant differences were observed in the mean N_{min} contents between the different zones in the 0-75cm soil layer (Fig. 3c). However, in the soil depth 25-75cm, the mean N_{min} content of the willow and poplar zone was significantly higher, than in the other zones in the small paddocks. The mean N_{min} content of the willow zone had decreased considerably since November in the small paddocks. In the large paddocks the mean N_{min} content was significantly higher in the willow and poplar-zone compared to the other zones, not significantly different from the high contents in the small paddocks.

To sum up there was high content of N_{min} in the willow and poplar zone of the small paddocks in late August early September 2009. Contents of N_{min} increased considerable from late summer to late autumn. In April 2010 a considerable reduction in the amount of N_{min} had happened, especially from the soil of the small paddocks.

3.2.2 Mineral nitrogen in the topsoil of the small paddocks in November 2009

In November 2009, N_{min} concentrations were very variable in the soil of the sampling plots (Fig. 6). The highest values were found in areas planted with willow. A few samples in the miscanthus zone also revealed high contents of N_{min}. 84% of the total N_{min} consisted of NH_4-N.

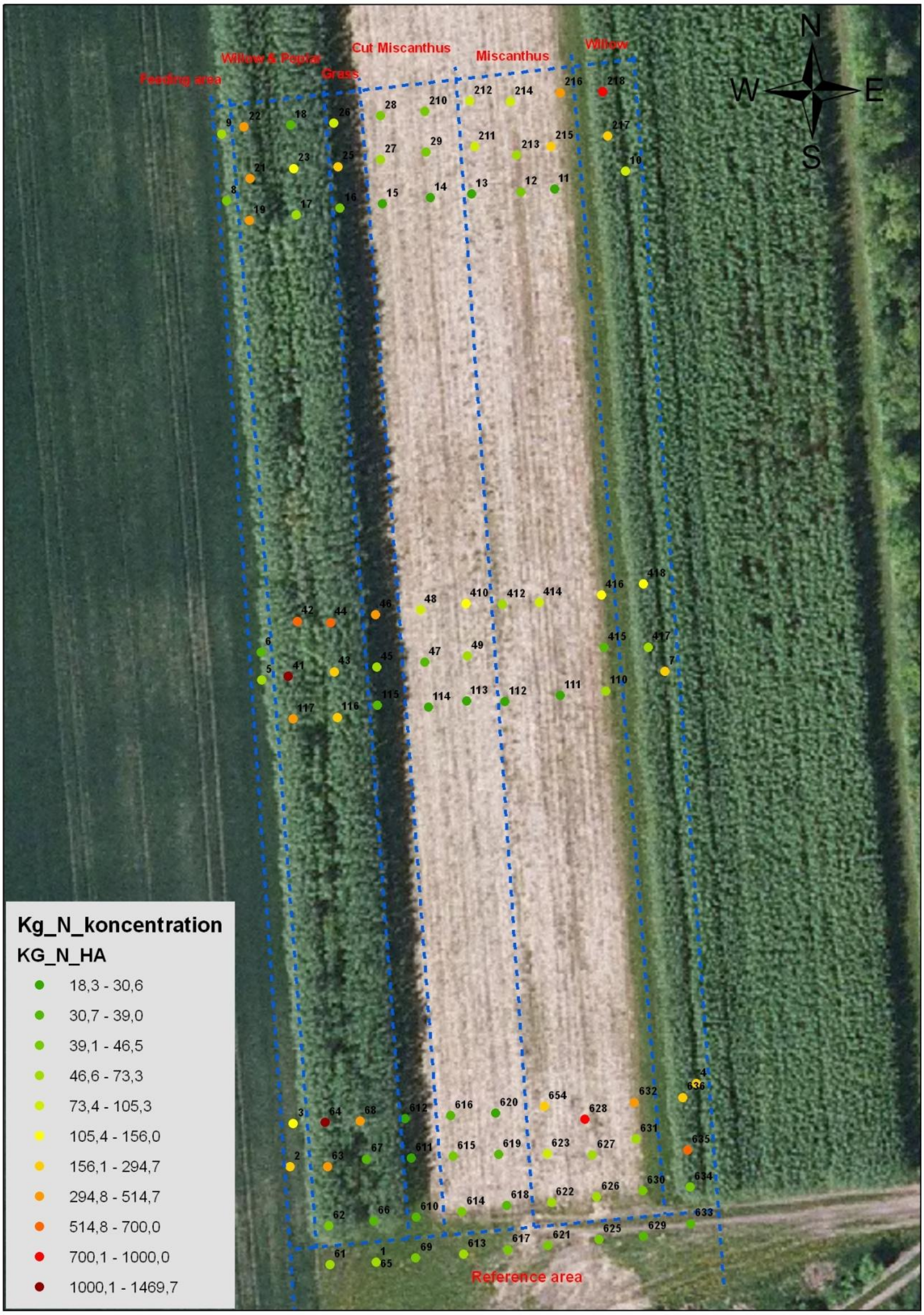


Figure 6 Distribution of N_{min} (kgN/ha) in the topsoil (0-25cm) in November 2009. The picture images the research area. N_{min} contents of the topsoil in the small paddocks are highlighted with different colors illustrating the different contents. Blue scattered lines illustrate a division into blocks.

Figure 7 shows the mean N_{min} contents of the topsoil of the different zones (blocks) of the small paddocks.

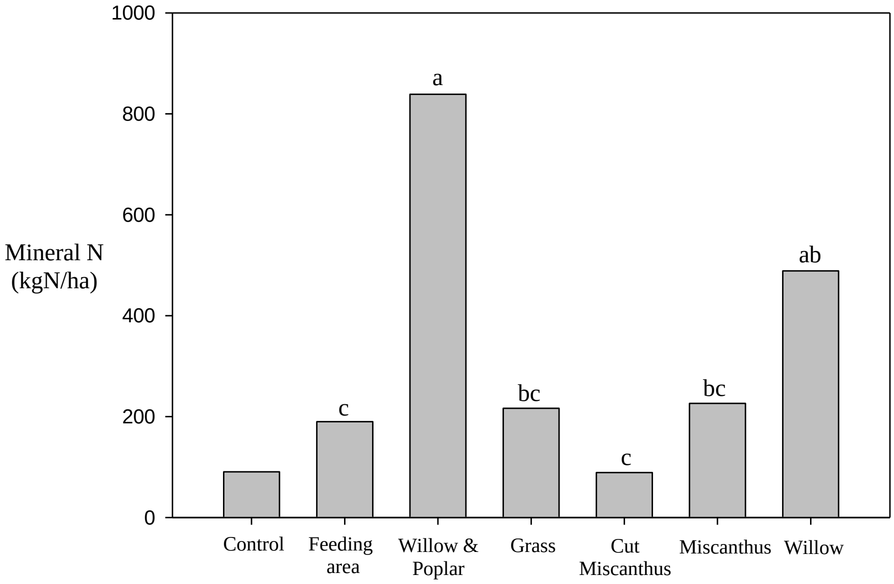


Figure 7 Diagram showing the mean content of N_{min} in the topsoil of the three small paddocks immediately after the pigs were removed. Means with the same letters are not significantly different ($P<0.05$). The control value is the mean of the samples taken outside the paddocks.

The mean N_{min} content of 839 kgN/ha in the topsoil of the willow and poplar zones is significantly higher than the soil content of the other zones apart from the mean N_{min} content in the zones planted with willow. The mean N_{min} content of the miscanthus zones is not significantly different from the mean content of the willow zone. The mean content of N_{min} in the topsoil of the grass zones differed from the mean N_{min} contents in the soil of the miscanthus- and willow zones at a 10 % level of significance ($P<0.1$).

Figure 8 illustrates the mean content of N_{min} in each zone within each of the small paddocks.

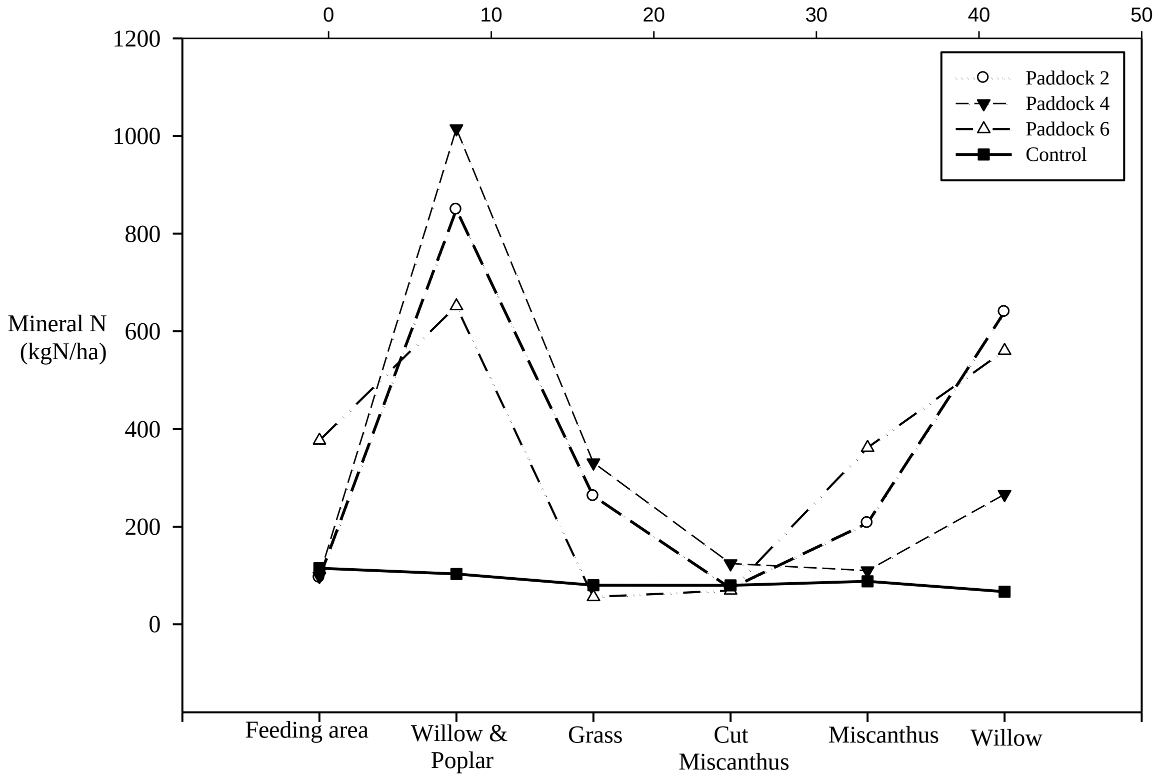


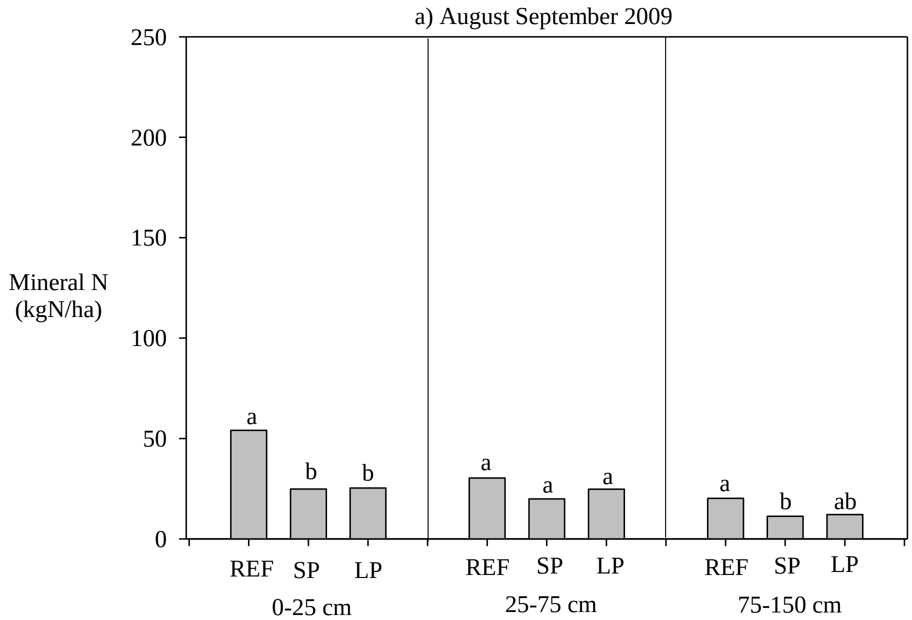
Figure 8 Diagram showing the mean content of N_{min} in the topsoil in each of the small paddocks. The control curve is not a mean, but the actual contents of N_{min} in the topsoil of the grass reference area outside the paddocks in the same block (see Fig. 6). In case of more than one reference sample in the same block the highest N_{min} content was chosen. Distances implied in the top axis of the diagram correspond to the distance to the feeding trough (in meters). The highest contents of N_{min} in the topsoil are measured about 6 and 45 meters from the feeding trough.

The N_{min} contents in the topsoil follow a regular system through the zones in each paddock. In two out of three cases the N_{min} content was relatively low in the feeding area. In all three paddocks the N_{min} contents increased significantly in the willow and poplar zone followed by a decrease to a lower level in the grass zone and the zone of cut miscanthus. The N_{min} contents increase in the miscanthus- and willow- zones. The highest contents of N_{min} in the topsoil are found at a distance of approximately 6 and 45 meters from the feeding trough.

Figure 6, 7 and 8 show high contents of N_{min} in the zones planted with energy crops.

3.2.3 Comparison of mineral nitrogen in the soil of different willow zones

The N_{min} distribution in the different soil layers did not depend on the willow zone (REF, SP, LP), since the variance analysis showed no significant interaction between willow zones and depths in the three measuring periods. In August/September 2009 and April 2010 there was a significant effect of depth ($P<0.01$) and a significant effect of willow zone at 6 % level of significance. However, in November 2009 no significant effect of soil depth was found, but a significant effect of willow zone at 6 % level of significance was found. Figure 9 illustrates the comparison of the soil mean N_{min} of the willow zones in each soil layer in the three measuring periods.



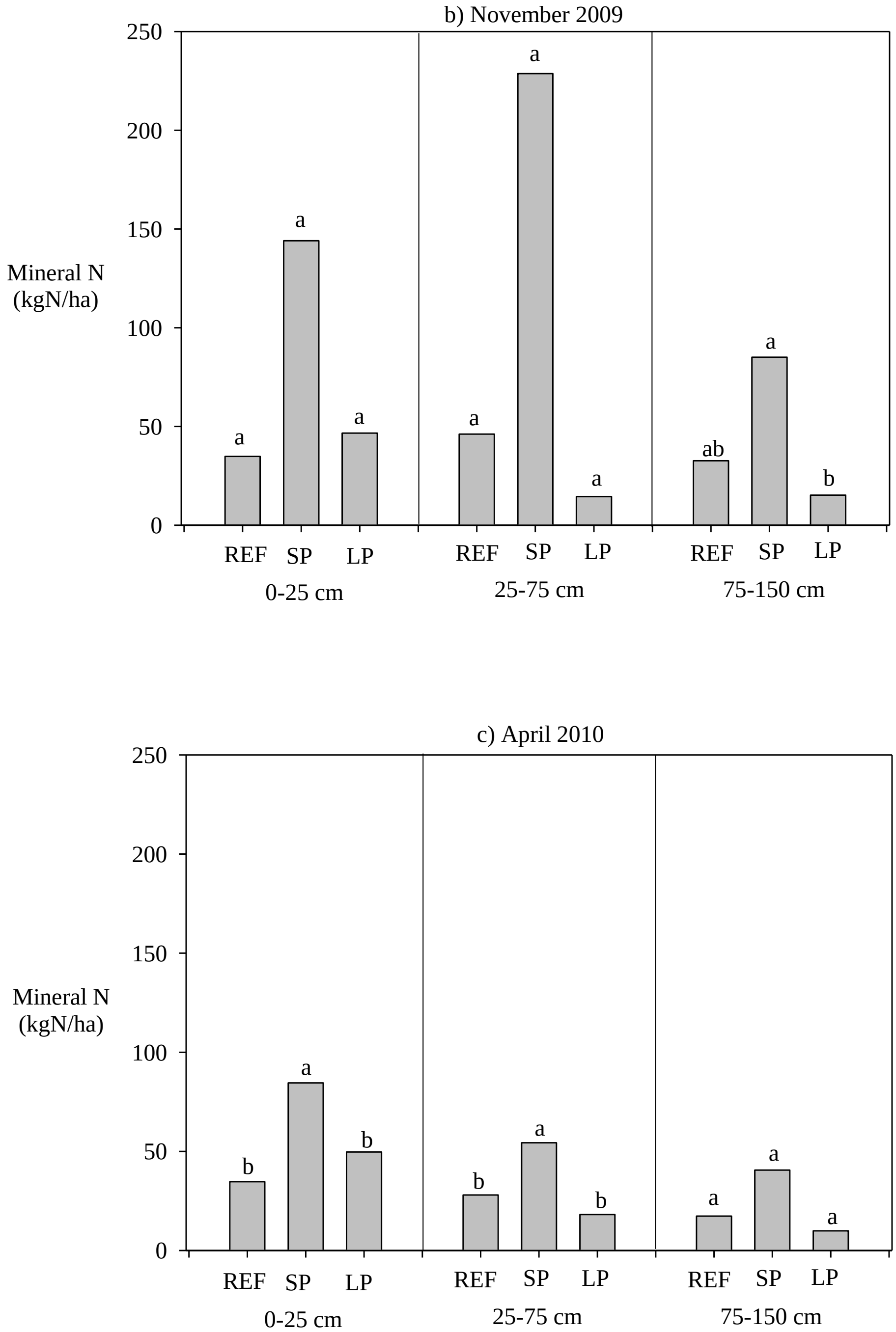


Figure 9 Mean contents of N_{min} (kgN/ha) in the three soil layers; 0-25cm, 25-75cm and 75-150cm of the zones planted with willow (SP, LP) and the reference zones planted with willow (REF). Means with same letters are not significantly different ($P<0.05$).

In late August early September 2009 the mean N_{min} content, of 54 kgN/ha in the topsoil of the willow reference zone (REF, r-plots in fig. 3), was significantly higher compared to the N_{min}

content in the willow zones of the small and large paddocks (Fig 9a). The mean N_{min} contents in the 0-25 cm and 25-75 cm soil layers in November are respectively more than 3 and 4 times higher in the willow zones of the small paddocks compared to the willow zones of the large paddocks and the reference willow zones (Fig 9b). However, the means are not significantly different. In the 0-25 cm soil layer, the mean N_{min} of the SP willow zones was significantly different from the other zones at 6 % level of significance. A high degree of variation was found in the soil N_{min} in November compared to the other two measuring periods. In April 2010 the mean N_{min} content was significantly higher in the willow zones of the small paddocks, in the 0-25cm and 25-75cm soil layers compared to the other willow zones (Fig.9c). In the same soil layers there was no significant difference between the large willow zones and the reference willow zones.

To sum up, the N_{min} contents were in most cases not significantly different between the willow reference zones and contents in the soil of the large paddocks. N_{min} contents varied considerably in the willow zones in November 2009.

3.3 Nitrogen balance

3.3.1 Water balance and potential nitrate leaching

Figure 10 illustrates the COUP simulation of the percolation in the soil of the willow reference area.

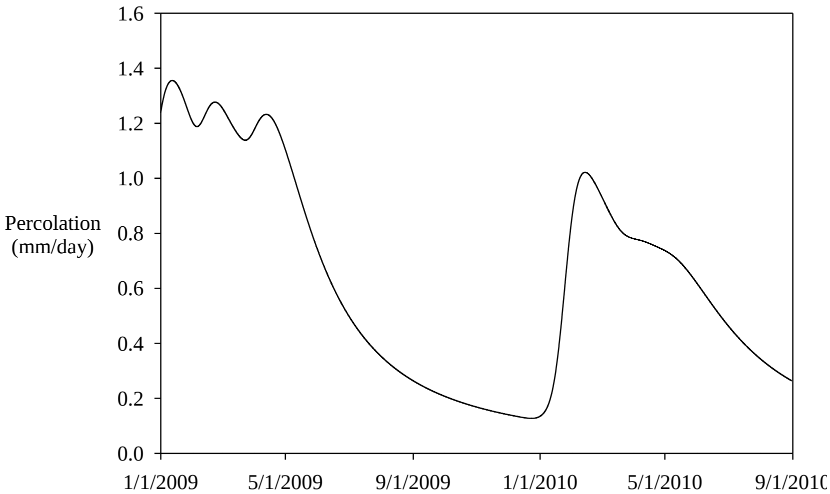


Figure 10 Simulation of the soil water percolation (mm/day) from the willow reference area from January 2009 to late August 2010

From January 2009 to late August 2010, two peaks of percolation were observed. Percolation was at a level between 1.1 and 1.3 mm/day from January 2009 to May 2009. From May 2009 percolation decreased to a level close to 0.1 mm/day in December 2009. Percolation peaked again in early February 2010 and from late February the decline began and continued slowly during spring and summer 2010. NO_3 concentrations of the soil water extracted from a depth of 175 cm of the willow reference area are illustrated in figure 11.

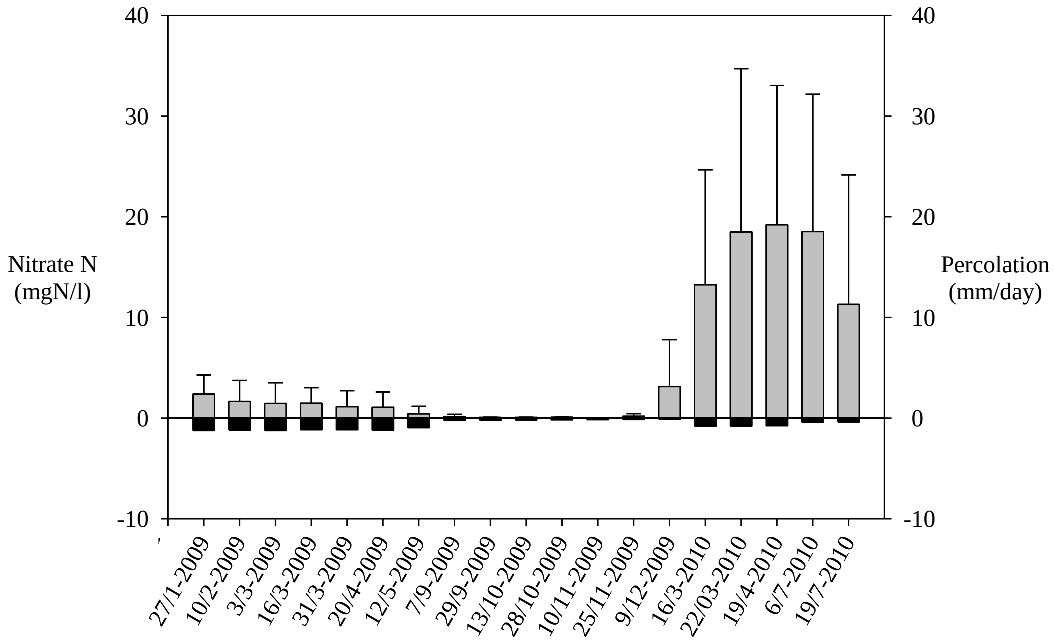


Figure 11 Mean NO_3-N concentration in soil water (grey bars) and percolation (black bars) in the soil at each sampling date in the willow reference area. Vertical lines indicate standard deviations.

When the investigation started in March 2009 NO_3 concentrations in soil water were generally at a low level (Fig.11). From May to September 2009 very low concentrations or no NO_3 were measured in the soil water. In the period from October 2009 and until late November 2009, there was often too little water sampled to measure the NO_3 concentration. However, if soil water was present low concentrations of NO_3 was measured. In December 2009 and during spring 2010, the mean NO_3 concentrations increased to between 3.1 and 19.2 mg NO_3-N/l. From November 2009 and April 2010 the NO_3 leaching was calculated to be 11 kgN/ha from the 0-175 cm soil layer. This was compared with the reduction of N_{min} contents soil layers of the willow reference area between November 2009 and April 2010 (Figure 12). In comparison the N_{min} analysis indicated a reduction of 33 kgN/ha in the 0-150 cm soil layer. This indicates roughly that 33 % of the N_{min} change could be estimated as NO_3 leaching.

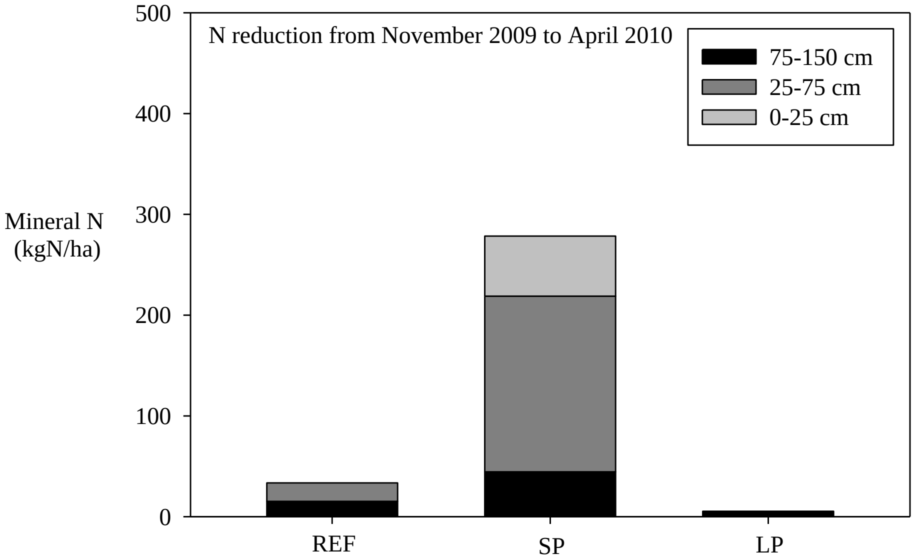


Figure 12 Difference between mean N_{min} contents measured in November 2009 and April 2010. The figure illustrates the change in soil N_{min} of the willow zones of the paddocks, and the willow reference area. Each color indicates the reduction of N_{min} in each of three soil layers.

A minimal reduction of N_{min} content was observed in the deep soil layer (75-150 cm) of the willow zones of the large paddocks (5 kgN/ha). However, there was a considerable change of N_{min} in each soil layer of the willow zones of the small paddocks from November 2009 to April 2010.

Figure 13 illustrates the mean contents of N_{min} from November 2009 to April 2010 in two soil layers of the investigated zones.

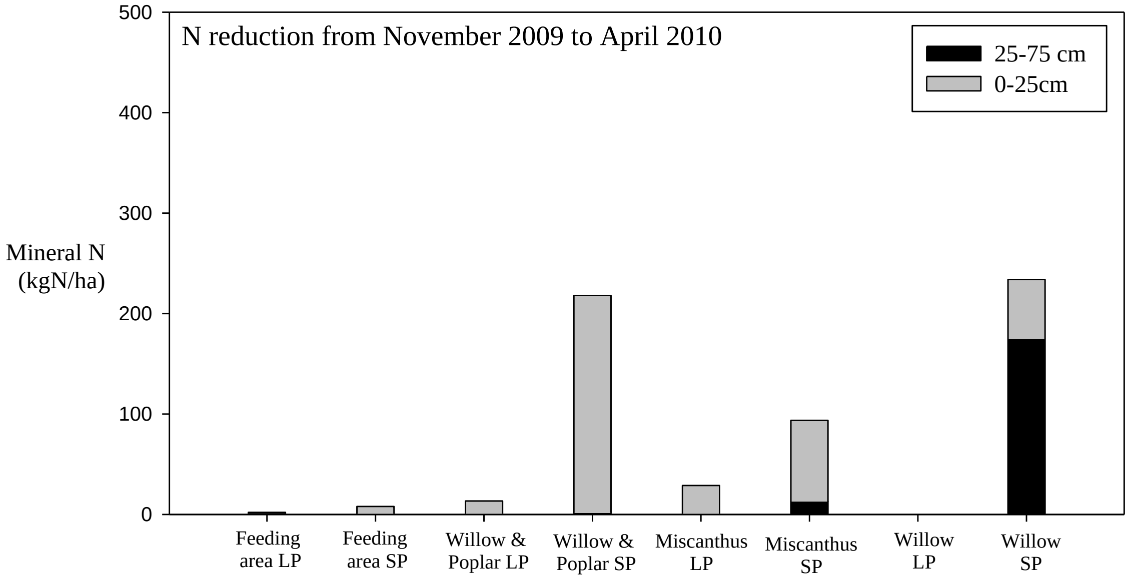


Figure 13 Difference between mean N_{min} contents measured in November 2009 and April 2010. The figure illustrates the change in soil N_{min} of the different zones, in the two soil layers 0-25 cm and 25-75 cm.

Pronounced changes of N_{min} were shown in the small paddocks, while there were no or relatively minor changes in soil N_{min} of the large paddocks. N_{min} reductions were generally observed in the upper layer of the soil except for the 25-75 cm soil layer of the willow zones of the small paddocks. The change in N_{min} contents were, of the 0-75 cm soil layer of the investigated areas between November 2009 and April 2010, 89 kgN/ha and 11 kgN/ha in the small and large paddocks respectively.

To sum up high concentrations of NO_3 were found in soil water in spring 2010 in the willow reference area. 33 % of the N_{min} change in the willow reference zone was estimated as NO_3 leaching. From November 2009 to April 2010 soil N_{min} was reduced especially in the small paddocks.

3.3.2 Crop nitrogen off-take

Table 3 summarizes N concentrations in plant material of the willow clones 'Jorr' and 'Bjørn' found by different investigators.

Table 3 Nitrogen contents in Miscanthus and Willow

Locality	Year & season of harvest	Year of establishment	Energy crop	N-Source	N-Concentration (% N in DM)	N-Content (kgN/ha)	Reference
Foulum	1995/Winter	1993	Jorr[a]	Mineral fertilizer (75 kgN/ha)	0.67	46 (64)[e]	Mortensen *et al.* 1998
Foulum	1995/Winter	1993	Jorr[a]	0 kgN/ha	0.70	61 (85)[e]	Mortensen *et al.* 1998
Gesten	1998/September	1997	Jorr	Sewage water (155 kgN/ha)	1.40	170	Unpublished data
Gesten	1998/September	1997	Bjørn	Sewage water (155 kgN/ha)	1.61	170	Unpublished data
Foulum	Average (93-95)/Spring	1990	Miscanthus	Mineral fertilizer (75 kgN/ha)[c]	0.59	45	Jørgensen 1997
Foulum	2009/August	2002 (1996)[b]	Miscanthus	N from pig manure SP [d] (186 kgN/ha)	0.81[f](SD 0.04)	143[f](SD 5.8)	Measured
Foulum	2009/August	2002 (1996)[b]	Miscanthus	N from pig manure LP [d] (58 kgN/ha)	0.70[f](SD 0.08)	129[f](SD 7.9)	Measured

a Mean N content in woody parts (stems and branches)

b Miscanthus was originally established in 1996, but rhizomes were harvested from the area in 1999 and 2002

c Applied 75kg N/ha in 1993 and 1995, but 110 kgN/ha in 1994

d N is unevenly distributed by pigs

e Estimated values for September harvest

f Mean of three paddocks

Mean N concentration in miscanthus plant material after harvest in August 2009 are registered in table 3. SD indicates standard deviations. Spring harvested miscanthus was investigated by Jørgensen (1997) from 1993 to 1995 and the average N concentration of the plant material from this investigation was included in the table. The highest concentrations of N were registered in a willow evaporation bed at the locality Gesten (55° 32´N, 9° 11´E). The young aged ‘Jorr’ and ‘Bjørn’ had crop N off-takes of 170 kgN/ha. The N concentrations of ‘Jorr’ at research center Foulum were not as high as in Gesten. In Gesten harvest was performed in September before defoliation. Mineral fertilizer did not have an effect on the N concentration of plant material at the Foulum locality. An affect of the higher supply of N in the small paddocks was observed in the N concentration of the miscanthus plant material.
To sum up, high N concentrations of willow plant material were shown in Gesten, while willow from Foulum had a lower N concentration of the plant material.

3.3.3 Nitrogen balance

Results quantifying inputs to and outputs from each pig system and the willow reference area are shown in table 4.

Table 4 One year Nitrogen balance

	Inputs (kgN/ha)		Outputs (kgN/ha)					
System	Feed/Fertilizer [a]	Atmospheric [b]	Leaching[c]	NH_3-N losses[d]	N_2O-N and N_2 emissions[e]	N retention in pigs[f]	Crop N off-take[g]	N accum.
Small Paddock	765	14	30 (89[c])	37	63	230	87	332
Large Paddock	241	14	4 (11[c])	12	20	72	60	87
Willow Ref.	240	14	11[h]	5	19	-	85	134

[a] The value of feed is average feed-N given in spring (protein 16.9%) plus average feed-N given in autumn (protein 16.7 %). 240 kgN/ha mineral fertilizer was given to the Willow reference area

[b] Estimated from the DEHM-model. The estimate is based on values from 2008 and Viborg was chosen as the municipal in the model

[c] Estimated from soil N_{min} analysis in 0-75 cm depth

[d] 7 % of N-content in manure and 2 % of N in NPK fertilizer (Andersen et al.,2001)

[e] Estimated from SimDen in 0-100 cm soil layer

[f] Average retention in each paddock. Retention of N is calculated as 30% of feed-N input

[g] Crop off-takes comprise miscanthus and willow in the paddocks and only willow in willow reference area

[h] NO_3 in soil water from 0-175 cm soil layer

The NH_3 volatilization per year is 25 kgN/ha higher in the small paddocks compared to the large paddocks. After 16 weeks with grazing pigs in the paddocks, the average N defecated from the pigs as manure is calculated to be 536 kgN/ha and 169 kgN/ha in the small and large paddocks respectively. This results in a total denitrification of 63 and 20 kgN/ha in the small and large paddocks respectively. The crop N off-take was estimated to be 27 kgN/ha higher in the small paddocks compared to the large paddocks. The pool of N accumulated in the soil was estimated to more than 240 kgN/ha higher in the soil of the small paddocks compared to the large paddocks.

4. Discussion

4.1 Defecation behavior of the pigs

According to Eriksen and Kristensen (2001) the highest contents of N_{min} are expected to be found in the feeding area. The registrations of defecation behavior of the pigs did not support this. There was a significantly higher manure deposition in the willow and poplar zone compared to the other zones in both measuring periods; spring and autumn 2009. At no point more than 10% of the defecation behavior was observed in the feeding area, while more than 43% was observed in the willow and poplar zone. Salomon et al. (2007) undertook comprehensive studies of the behavior of fattening pigs on pasture and found the highest number of defecations and urinations between huts and the feeding troughs indicating that these systems may suffer from uneven distribution of nutrients (Salomon et al., 2007). This was also the case in our investigation, since the willow and poplar zones were positioned between the feeding area and the hut. However, during autumn the pigs were observed sleeping in the willow and miscanthus zones, not using the hut much. The consequence of season should be further investigated. The pigs may use the hut when the temperature is low which might influence defecation behavior. Salomon et al. (2007) assumed that the pigs would prefer to defecate and urinate near their resting place and found that they defecated 1-15 m from this place which seems to be the case in our investigation. In other investigations sows preferred to defecate and urinate in a zone between 5 and 15 m from nesting sites (Stolba and Woodgush, 1981). Stern and Andresen (2003) found that areas with huts, drinking points and wallows were used for defecation (Stern and Andresen, 2003) which was not observed in our investigation. Fraser and Broom (1990) did however find excretory behavior of fattening pigs which could explain the behavior of the pigs in our investigation. Fattening pigs in housing systems tend to defecate and urinate in certain areas close to pen walls, orientated parallel to or with their hindquarters towards the wall (Fraser and Broom, 1997). This indicates that pigs seek protection from predators or other pigs when they defecate and urinate. This could explain why pigs prefer to defecate in the willow and poplar zone instead of the open feeding area. In semi-natural environments the border of a forest is an important area of activity (Stolba and Woodgush, 1981). Most nests are built in moderately sheltered sites to avoid wind and sun. It appears that pigs also seek an open view as well as shelter (Stolba and Woodgush, 1981). Energy crops like willow and miscanthus can provide these environmental features that might stimulate the pigs to prefer these areas as resting regions. Even though the pigs preferred to defecate in the energy crop areas in our investigation, a difference between the behavior of sows and finisher pigs cannot be excluded. High soil N_{min} levels close to feeding sites can be caused by the fact that sows receive large quantities of feed (Braund et al., 1998). Sows receiving large amounts of food lie down soon after feeding and spend less time grazing. The reduction in foraging behavior and the larger amount of time spend in the feeding area can cause more urine and feces to be deposited here (Braund et al., 1998). It would be relevant to investigate the same system with sows to see if the N distribution would be different.

The observation of defecation behavior in our study only provides a snapshot of the deposition of feces and urine. It was not a 24-hour investigation and observations were only done 2 days a week. The observations of the defecation behavior should therefore be compared with the N_{min} concentration of the soil in order to describe the distribution of N_{min} in the soil of the paddocks.

4.2 Distribution of mineral nitrogen

4.2.1 Average mineral nitrogen of the soil in the different zones

Even before the pigs were let out in the paddocks in September 2009 the mean contents of N_{min} in the soil were dissimilar in the different zones (Fig. 5a). A consequence of the high defecation behavior in the willow and poplar zone after the first investigation session from March to May 2009 was shown by the higher mean N_{min} content in this particular zone in August/September 2009 (Fig. 4). This illustrates that N hot spots are not only affected by the current, but also previous livestock (Salomon et al., 2007). The large paddocks did not seem to be as affected of the history of pig production, here no distinctive difference between zones was observed. In November the high mean N_{min} contents in the topsoil of energy crop zones correspond to the observed defecation behavior in these zones (Fig. 4). Large concentrations of N_{min} in the soil in autumn are of major concern since they may lead to NO_3 leaching (Williams et al., 2000). Figure 14 shows the net increase of N_{min} in the soils of the paddocks from late August early September to November 2009.

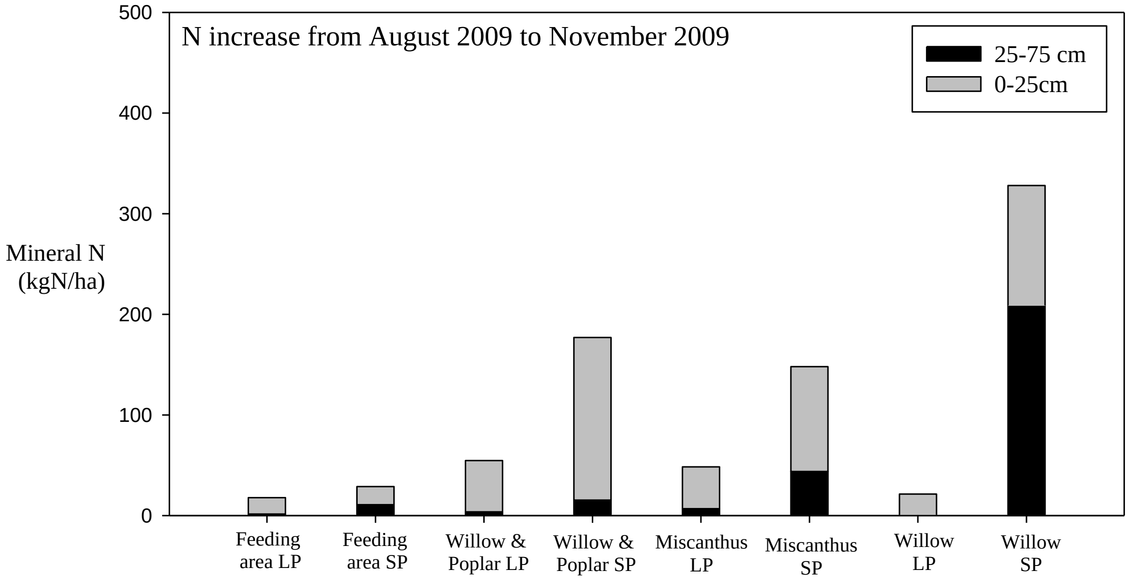


Figure 14 Prepared from figure 5a and 5b. Shows net increase of N_{min} in the soils of the paddocks from August/September to November 2009.

N_{min} could potentially be leached from September to November 2009, but is not likely in this case since precipitation and percolation in this period were relatively low (Fig. 2 and 10). From figure 14 it is clear that the zones of the small paddocks (except for the feeding area) were supplied with high amounts of N. The high mean N_{min} content in the 25-75 cm soil layer of the willow zones of the small paddocks reflects that there was a high degree of variation of N in the soil samples of this zone.

The large paddocks were not as affected with N_{min} hot spots as the small paddocks were. This indicates that reduced stocking density can be used as a management tool to reduce NO_3 leaching. The change in the N_{min} contents in the 0-75cm soil layer during winter 2009/2010 in the investigated zones of the paddocks will be further discussed in part *4.1.5*.

4.2.2 Mineral nitrogen in the topsoil of the small paddocks in November 2009

Because of the frequent defecation behavior in the willow and poplar zones, these zones received excessive amounts of N_{min} (Fig. 6). The highest contents of N_{min} probably reflect areas of urine excretion. The high amount of NH_4-N in the soil samples might reflect urine spots where urea-N rapidly changes to NH_4-N and then in a slower rate to NO_3-N. The proportion of N_{min} present as NH_4 depends on time, moisture content and temperature (Eriksen and Kristensen, 2001). Defecation behavior was evidently linked to the zones planted with energy crops, since these zones contain high values of N_{min} in the topsoil. Figure 8 illustrated that this behavior was very systematic. The fact, that N_{min} contents in the feeding areas were close to the content in the control area, supports the low percentage of observed defecation behavior in the feeding area (Fig. 4). Eriksen *et al.* (2002) found that N_{min} levels in soil decrease with the distance to the feeding site. At 30-40 m distance, N levels were similar to the reference area (Eriksen et al., 2002). This was not the case in our investigation. According to figure 8, the highest contents of N_{min} were found respectively 6 m and 45 m from the feeding trough. Both areas associated with energy crops, indicating that they can be used as a management tool to influence defecation behavior of free range pigs. It could be discussed, which factors determined the defecation behavior of the pigs. Since, high concentrations of N were found in both miscanthus zones and willow zones it is not likely that the pigs had distinct preferences for one type of energy crop. Because of the significantly higher N concentration in the soil of the willow and poplar zone it was obvious that the placing of the feeding through had a clear effect on the preferred energy crop zone for defecation. Defecation behavior was determined by a combination of distance to the feeding trough, energy crops used as protection during defecation and probably also the resting place. This knowledge can be used to optimize the distribution of urine and feces from the pigs. By regularly shifting the position of the feeding trough and maintain it in a relatively close distance to areas planted with energy crops it would probably be possible to influence the distribution of N in a paddock. It might also be possible to introduce new areas of energy crops to the paddocks to ensure that feces and urine are more evenly distributed over the land area. An earlier investigation showed that newly allotted areas were used intensively for foraging and defecation behavior (Stern and Andresen, 2003).

4.2.3 Comparison of mineral nitrogen in the soil of different willow zones

N_{min} contents in willow zones were not high in the measuring period August/September 2009 (Fig.9a). The high mean N_{min} content measured in the topsoil of the reference willow zones is probably a result of the mineral fertilization with 240 kgN/ha in April 2009 compared to 58 kgN/ha and 186 kgN/ha, excreted by the pigs in the large and small paddocks, respectively, in spring 2009 . Since no significant difference was found between the small and large paddocks and the reference willow plots in the 25-75 cm soil layer, the significant difference between the low N_{min} contents in the 75-150 cm soil layer is probably caused by soil N_{min} variation. Considerable higher variation estimates in the November measuring period indicate that the statistical strength of the test is much lower in the measuring period November compared to the other measuring periods. The variable defecation behavior of pigs supports the variation found in N_{min} contents. Even though, pigs prefer to defecate in energy crops, there seems to be a difference between each group of pigs in the paddocks in which energy crop zone they choose for defecation. In most cases the N_{min} contents of the reference willow area and the large paddocks are not significantly different. This provides a potential of drawing parallels between the NO_3 leaching risk from the reference willow and the large paddocks. Still, it should be kept in mind that the pigs distributed the feces and urine unevenly and had a preference for the willow and poplar zones. However, no significant difference was found in the mean N_{min} contents of the 0-75 cm soil layer between the willow poplar zones and the willow zones of the large paddocks in the measuring periods August/September 2009 and November 2009.

4.3 Nitrogen balance

4.3.1 Water balance and potential nitrate leaching

The prolonged growth period of the willow clone 'Bjørn', was proven by the low percolation during late summer and autumn 2009. The low percolation is partly caused by the high water use in willow (Jorgensen and Schelde, 2001). Percolation during winter 2009/2010 was relatively low because of low temperatures from the middle of December 2009 to April 2010 (Fig. 2). Winter 2009/2010 did not reflect a 'worst case' situation. A mild winter, with temperatures above 0 ºC and high precipitation, is expected to cause a higher degree of percolation and thereby a higher risk of NO_3 leaching. Melt water from the heavy snowfall in winter 2009/2010 probably affected percolation, during spring 2009, creating a risk of NO_3 leaching. There was a considerable N_{min} content in the willow reference area, during summer 2009, probably because of the 240 kgN/ha mineral fertilizer applied in spring 2009. Because of little percolation until next spring N_{min} was not transported to the suction cups until spring 2010 and was here reflected in the higher NO_3 concentrations in the soil water. Standard deviations illustrate the high variation between the measuring points. Variation between suction cubs is natural, since the water samples are sampled from a small volume. It illustrates that replications are important and the six suction cubs in this investigation were an absolute minimum number. Preliminary investigations indicate that mineral fertilization of willow with 140 kgN/ha, will not create a risk of N leaching, but a supply of 280 kgN/ha might result in a considerable amount of N being leached (Riber, 2010).

The high reduction of soil N_{min} estimated from the small paddocks between autumn and spring indicates that, even though, energy crops may assimilate N excreted by the pigs after the first investigation period in spring, they are not able to absorb mineralized N from spring plus the N defecated in the second investigation period in autumn. As a response to critical periods of leaching, it is relevant to consider how to prevent high concentrations of NO_3 in the soil, particularly towards or during drainage season. This impact may be reduced by taking the stock off the paddocks in the autumn-winter period. Water use in willow is under all circumstances higher than in grass (Jorgensen and Schelde, 2001). Because of the high water use in willow during summer and autumn soil water content can be very low in the start of winter and will take some time to replenish before NO_3 is leached. An earlier investigation of loamy sand soil revealed a reduction of 150 kgN/ha in soil N_{min} from autumn to spring in the 0-40 cm soil layer (Eriksen and Kristensen, 2001). This experiment was carried out in a paddock with grazing farrowing sows for approximately six months at a high stocking rate. In comparison the small paddocks with a similar stocking density had a N_{min} reduction of 89 kgN/ha in the 0-75 cm soil layer from autumn to spring. This indicates that the soil N_{min} pool with a potential of being leached, as $NO_{3,}$ is much smaller in paddocks planted with energy crops compared to a grass field, taken the potential difference between sows and finisher pigs into consideration.

Another positive side effect is the persistence of perennial energy crops, compared to grass. Williams et al. (2000) found that the concentration of NO_3-N in the drainage water from an area increases as pigs progressively destroy grassland. The perennial energy crops in our investigation persisted and grew during the whole summer period.

4.3.2 Gas emissions from the paddocks

Potential fodder spill in the feeding area is not considered in this investigation. Fodder spill will result in less manure produced and a small overestimation of the rates of denitrification and NH_3 volatilization calculated. SimDen is developed to estimate denitrification from conventional crop systems, which might result in some considerable uncertainties on the estimates of denitrification. However, it is presumed that the substantial larger amount of denitrified N in the small paddocks is correct.

A constant emission coefficient was used to estimate NH_3 volatilization. It can however, be problematic to use a constant emission coefficient over time because of the changeable ratio between NH_3-N and total-N over time (Andersen et al., 2001). NH_3 volatilization is only sporadically clarified for grazing pigs, and NH_3-N is a standardized value in this study depending on the feed-N input. Feed-N input is the variable with the largest affect on NH_3 volatilization (Sommer et al., 2001). It should therefore be considered if it is possible to reduce the amount of feed given to grazing pigs, without risking reduced growth of the pigs and manipulation of the energy crops. In the measuring period March-May the pig were on average given 22 % less feed compared to the pigs in the measuring period September - November and the energy crops survived in spite of this. NH_3 volatilization is influenced by incident solar radiation, precipitation, pH, wind and temperature (Sommer et al., 2001). Since the willow and poplar zones were found as preferred defecation areas, NH_3 volatilization from these zones was expected. The open space between the rows of willow, with no short plant cover at the soil surface, may enhance a risk of NH_3 volatilization from the soil surface. However, the height and denseness of willow reduces wind speed and radiation from the sun, which inhibits NH_3 volatilization. The remaining NH_3-N in the soil, which is not volatilized may be converted by nitrifying bacteria to NH_4-N and contributes to the soil N_{min} pool (Jarvis et al., 1996). The NH_4-N will be available for plant uptake, but could also be converted to NO_3-N. If NO_3-N is not absorbed by plants or microorganisms it constitutes a risk of NO_3 leaching. NH_3 volatilization from plants is most often considered below 5 kgN/ha (Andersen et al., 2001) and is ignored in this investigation.

4.3.3 Crop nitrogen off-takes

Miscanthus giganteus

A miscanthus crop requires several years to become established in the Danish climate, but at high planting densities (4 plants/m^2) the maximum yield level can be reached in the second or third growing season (Jorgensen, 1997b). Miscanthus should therefore have an establishment period of two to three years, before pigs are put into paddocks planted with miscanthus.

Due to significant winter losses of leaves and upper stems from miscanthus in Denmark caused by the frost, the yield is more than halved when it is harvested in the spring (Jorgensen, 1997a). As the mineral concentrations are highest in the lost fractions (Jorgensen, 1997a), harvest in spring would cause a lower % N in DM than harvest in autumn.

Miscanthus retranslocates N in the leaves and stems to the rhizomes (storage and reproductive organs) in winter and this influences the % of N in DM in the spring (Marschner, 1995). Plant samples of miscanthus harvested in August 1994 had a mean N content of 135 kgN/ha in the above ground standing stock (Jorgensen, 1997a) corresponding to the measurements done in this investigation. A relationship between N application and N concentration in plant material has earlier been reported (Schwarz et al., 1993), and seems also to be the case in our study. Still it should be kept in mind that the application of N, in the paddocks is not equally distributed by the pigs. Miscanthus samples were harvested in August 2009, before the introduction of the second session of pigs. It is therefore only supplied with half of the total year N supply. Concentrations of N in plant material in October 2009 might therefore be higher. Crop N off-take at spring would be more than halved compared to August harvest, but a lot of the nutrients would probably be stored in the rhizomes. Miscanthus plant material, harvested in August has a high water content, which call for use in biogas (Uellendahl et al., 2008) or in a biorefinery (Hayes and Hayes, 2009) instead of combustion. The energy spend on drying is still lower, than the higher amount of energy produced (higher dry matter production) (Jorgensen, 1997a).

If the N surplus is high in a pig paddock planted with miscanthus, creating a risk of NO_3 leaching, harvest in August should be considered in order to remove N by high crop N off-take.

Willow

During the establishment of willows there is a risk of NO_3 leaching (Mortensen et al., 1998). Willow should therefore establish 2-3 years before pigs are put into willow paddocks.

The high concentration of N in the plant material of Gesten willow was probably caused by the high availability of nutrients in the willow evaporation bed, the young steams and the high plant density. This might result in an overestimation of the N concentration in the willow plant material of the small paddocks. However, the N supply to the small paddocks was larger than the contribution of N to the willow evaporation bed, which might compensate for the overestimation. From Mortensen et al. (1998) the highest N concentration in plant material was chosen for further analysis in the N balance of the large paddocks. The N concentration might, however, be underestimated because of the lower N supply. Mortensen et al. (1998) found no effect of fertilization on the concentration of N in the plant material, however, the large paddocks were supplied with 40 kgN/ha more than the willow in Mortensen et al. (1998). Seasonal differences between years cannot be ruled out.

Values of crop N off-take should be used with concern, because they can easily be influenced. In woody crops NUE depends significantly on the length of the harvest cycle which, changes the ratio between nutrient-rich bark and the stem-wood. Earlier studies indicate that the NUE of N increases in willow clones from annual harvesting to a 3-year rotation (Adegbidi et al., 2001). Other studies however only find this increase for the nutrient phosphorous (Lodhiyal and Neelu, 1997). In order to have a high crop N-offtake, summer harvest is a possibility but methods of harvest needs further development.

4.3.4 The unified nitrogen balance

It is difficult to establish straightforward relationships between nutrient management, surplus, losses and environmental impact. An N balance is useful as a screening tool providing a method to calculate values of N in a system. It should however be kept in mind, that several processes is regulating nutrient dynamics, and the N balance may need complementary understanding of these processes (Oborn et al., 2003).

The atmospheric deposition of N was in 2008, 14kgN/ha in the investigation area. This value is affected by the weather and might deviate from the 2008 value in 2009, but only small values compared to the rest of the N balance.

It is obvious from the N balance that the stocking density has an influence on the system of pig paddocks planted with energy crops. Per pig a high stocking density increases the risk of NO_3 leaching and the pool of accumulated N in the soil will be higher.

There was a difference between estimated NO_3 leaching from N_{min} analyses of soil and the soil water concentration. It is possible that the willow roots assimilate NO_3 from the 150-175cm soil layer. Also denitrification could happen in the deep soil layers, but on the other hand it is also possible that a higher amount of N than originally measured was mineralized in the soil. It should be considered that the estimated contents of N leaching from the paddocks are rough estimates. The assumption of 33 % of the N_{min} reduction being NO_3 leaching is a rough indication because N is supplied in both organic and inorganic forms in the paddocks, and at a different time compared to the willow reference area.

N_{min} analyses were not done in the grass zones and the zones with cut miscanthus (35 % of the investigated area). This might result in an underestimation of the amount of N leached from the paddocks. However, very little defecation behavior was observed in the open areas. In order to increase DM yield from energy crops in the paddocks it would be possible to plant the open areas (grass and cut miscanthus areas), with energy crops. This would probably not reduce leaching from N hot spots, but might enlarge the area of defecation. The crop N off-take however depends on the season of harvest, which could also be used as a tool to regulate N contents of the soil. Harvest of Miscanthus in late summer could increase the crop N off-take up to 50%. N uptake in grass was not included as a factor reducing NO_3 leaching, because an earlier investigation showed, that trampling and rooting behavior of pigs can completely destroy well established grass cover exposing the bare soil, with a result of no crop N uptake (Williams et al., 2000). Some of the grass, however, did survive, which might reduce NO_3 leaching. The pool of N in the soil is expected to be high, because of the N-contribution from the amount of grass-, plant- and root material. The importance of only keeping pigs on arable land every second year at high stocking densities, is obvious from the result of the high pool of N accumulated in the soil in the small paddocks. The pool of organic bound N is left for mineralization affecting NO_3 leaching the following years.

5.1 Conclusions

From observations of defecation behavior of pigs, feces and urine are unevenly distributed in pig paddocks. Pigs did not have preferences for defecation in the feeding areas. Defecation behavior was observed in a significant higher degree in the willow poplar zone 6 meter from the feeding through. This is supported by N_{min} soil analyses from the area which reveal high N_{min} contents in the zones planted with energy crops. Energy crop zones are susceptible for becoming N hot spots with increased risk of NO_3 leaching from the soil, especially during mild winters. The influence of stocking density is pronounced, and result in NO_3 being leached from the small paddocks. From an environmental point of view, seasonal production (late winter to late summer) of fattening pigs, when nutrient assimilation in the energy crops is high and percolation in the soil is low, is a viable option in order to reduce NO_3 leaching. Another possible strategy is a reduction in stocking density during autumn and winter, a strategy that calls for careful management to avoid uneven distribution of N. Defecation behavior might be influenced by regularly changing the placing of the feeding trough or introducing new areas of energy crops. These views should be further investigated. However, when precautions are taken, this investigation indicates that it is possible to combine energy crop production with free range pig production with limited NO_3 leaching. N leaching from the paddocks planted with energy crops, 30 kgN/ha and 4 kgN/ha roughly estimated from the small and large paddocks respectively, was not as high as N leaching from sows on grassland and the energy crops were more persistent compared to grass.

6.1 Perspectives

Keeping pigs on pasture carries a high risk of environmental damage because of N loss. The most acceptable way of keeping pigs on pasture involves a combination of reduced dietary N intake, reduced stocking rate and seasonal rather than round year production. Since energy crops are preferred as defecation areas they could potentially be used, as a management tool manipulating the defecation behavior of the animals. Energy crops could also be used as a favorable alternative to nose ringing of free range sows, which conflicts with natural behavior of sows (Eriksen et al., 2006b). It is possible to imagine a three year rotation of willow where a single session of pigs is introduced (in summer to reduce NO_3 leaching) to the willow area in the second and third year of growth. Renewable energy output from organic farming in Denmark is currently lower than from conventional farming (Jorgensen et al., 2005). However, utilizing 5 % of the agricultural land for short rotation coppice to biogas could produce energy equaling 30-58 % of the energy input for organic farming (Jorgensen et al., 2005). Recycling of N is of tremendous value for organic farming. Biogas plants or biorefineries provide new opportunities and makes energy crop production favorable. Some of the demands of recycling nutrients may be accommodated in a combined system of energy crop- and free range pig production.

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Appendix

Appendix 1: Soil texture at the locality Foulum

Table Appendix 1: Texture of the soils in different layers at the locality Foulum. Mean of samples from three blocks. Standard deviations (SD) are mean of all layers. Originally from Mortensen el al. 1998

Fraction size and content in percentage weight					
Depth (cm)	Clay (< 2 µm)	Silt (2-20 µm)	Coarse silt (20-63µm)	Sand (63-200µm)	Coarse sand (200-2000 µm)
0-20	8.2	9.1	17.0	32.1	27.9
20-40	8.2	10.7	14.5	33.5	28.6
40-60	10.1	12.2	13.1	31.2	30.2
60-100	13.1	12.2	13.6	31.5	28.4
100-135	14.6	11.6	12.2	30.9	30.3
SD	0.7	1.6	1.7	2.1	2.1

Appendix 2: Clones of poplar

P-1	P. EUROAMERICANA
P-2	P. GENEROSA
P-3	P MAXIMOWICZII X P. TRICHOCARPA 'ANDROSCOGGIN
P-4	P. KOREANA X P. TRICHOCARPA
P-5	P. TRICHOCARPA X P. KOREANA
P-6	P. x BEROLINESIS
P-7	P. x BEROLINESIS X P. MAXIMOWICZII
P-8	P. x BEROLINESIS II (ZEHUSICE)
P-9	P. BALSAMEA X P. AURIFOLIA
P-10	P. x BEROLINESIS X P. MAXIMOWIC 211 'OXFORD'
P-11	P. BALSAMEA X P. TREMALA

Appendix 3: Behavior registration table

Adfærdsregistrering

Skema 2060

Dato: ________ **Hold:**_________ **Vejr:** __________ **Vind:** __________ **Temperatur:** _________

KL. →														
Område	Adfærd	Antal	Adfærd	Antal	Adfærd	Antal	Adfærd	Antal	Adfærd	Antal	Adfærd	Antal	Adfærd	Antal
Zone 1														
Zone 2														
Zone 3														
Zone 4														
Zone 5														
Zone 6														
Zone 7														
Zone 8														
Ude af syne														

Koder

Vejr:
- Sol = 1
- Letskyet = 2
- Overskyet = 3
- Let regn = 4
- Regn = 5

Vind:
- Vindstille = 1
- Let = 2
- Jævn = 3
- Kraftig = 4

Adfærd:
- Hviler = 1
- Æder = 3
- Går, slår = 4
- Græsser = 5
- Roder i jorden = 6
- Manipulerer pil, poppel m.m. = 7
- Manipulerer elefantgræs = 8
- Andre aktiviteter = 9
- Afsætter fæces = 21 Hele perioden
- Afsætter urin = 22 Hele perioden

Appendix 4: Equipment for soil sampling

Appendix 5: Grid values

Table Appendix 5: Grid values for each of the studied zones

Zone number	Grid for small pens (m)	Grid for large pens (m)
1	2,5 x 1,125	8,6 x 1,125
2	2,5 x 1,8	8,6 x 1,8
3	1 x 1,8	
4		1 x1,8
5	2,5 x 2,4	8,6 x 2,4
6	2,5 x 1,2	8,6 x 1,2

Appendix 6: Reactions in Autoanalyser

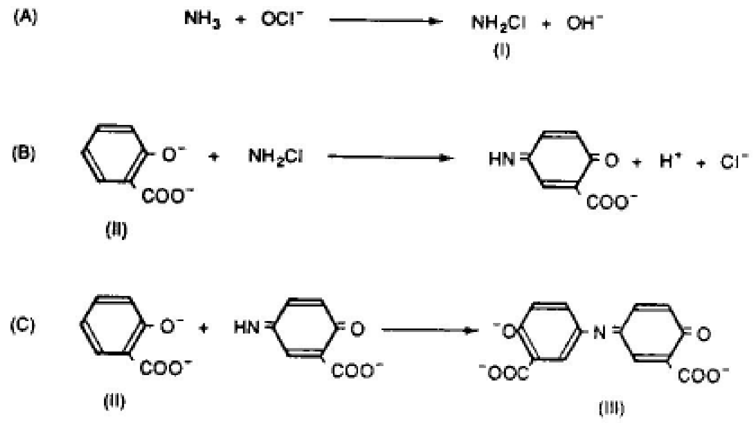

Fig. 38–3. Reactions in method for colorimetric determination of NH_4^+: (*A*) monochloramine (I) formation; (*B*) oxidative imination of salicylate (II); (*C*) coupling reaction to form indophenol dye (III).

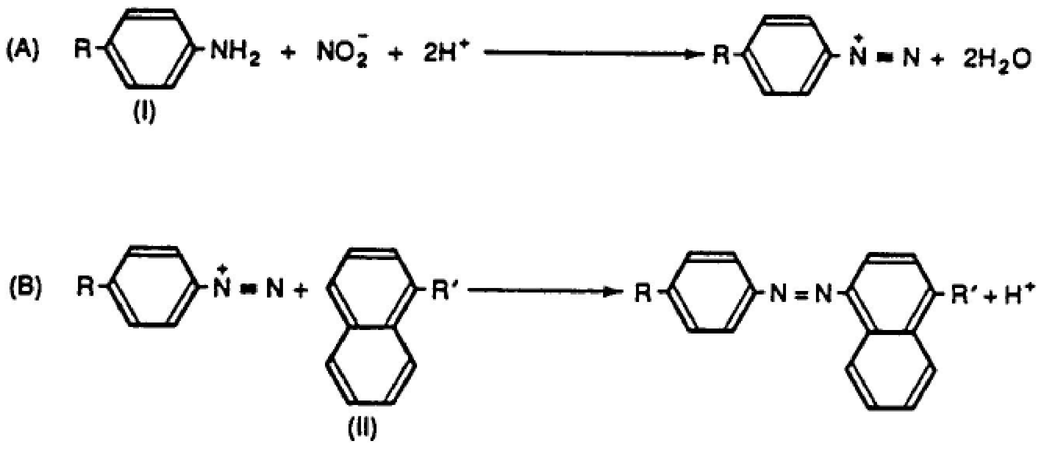

Fig. 38–4. Diazotization and coupling reactions in method for colorimetric determination of NO_2^-: (*A*) diazotization reaction-(I) sulfanilamide ($R = -SO_2 \cdot NH_2$); (*B*) coupling reaction-(II) *N*-(1-naphthyl)-ethylenediamine ($R' = -NH \cdot CH_2CH_2 \cdot NH_2$).