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NITRATE LEACHING DURING ESTABLISHMENT OF WILLOW (*SALIX VIMINALIS*) ON TWO SOIL TYPES AND AT TWO FERTILIZATION LEVELS[1]

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Abstract—The production of willow in short rotation is expected to result in low nitrate leaching losses as is the case with other permanent crops. However, there is a risk of leaching of nitrate during establishment when the plant cover is limited. Nitrate leaching was followed for three years from the establishment in 1993 of willow (*Salix viminalis*) at two sites, a coarse sand at Jyndevad and a loamy sand at Foulum. Two levels of nitrogen, 0 or 75 kg N/ha in NPK, were applied annually, though only 38 N/ha was applied in the first year.

Leaching was calculated from usually weekly measurements of the nitrate concentration in soil solution and relating with the amount of percolation based on measured precipitation and changes in the soil water content over the sampling periods. Mean leaching for the three periods 1993–94, 1994–95 and 1995–96 amounted to respectively 142, 61 and 0 kg N/ha at Foulum and to 130, 9 and 4 kg N/ha at Jyndevad. The high leaching in the first year was caused by an unusually high content of mineral N in the soil at the start of the experiment. The absence of any leaching 1995–96 at Foulum was due to very low precipitation and a consequent lack of percolation. For the first period (1993–94) the fertilized treatment increased leaching by 32 kg N/ha compared to no fertilizer as a mean of the two sites, while the difference for the following two periods was reduced to 1–2 kg N/ha. It is concluded that application of nitrogen should be avoided in the year of planting of willows, while in the following years 75 kg N/ha can be given without risk of increased leaching.

Keywords—Willow; nitrate; leaching; soil type; N-balance.

1. INTRODUCTION

The Danish Action Plan on the Aquatic Environment[1] from 1987 was enacted with the aim of halving the loss of nitrogen from agricultural production to the aquatic environment, mainly by trying to increase the nitrogen efficiency in conventional agricultural crops. Another method to obtain this could be by change of land use. The most efficient change is into permanent crops so that annual soil tilling and periods without a deep root system are avoided. The mean annual leaching of nitrate from intensive grass production is estimated at 17 kg/ha compared to 69 kg/ha from a grain crop rotation.[2] Leaching from fallow grass is found to be less than 10 kg/ha[3] and from established forests 0–16 kg/ha.[4]

Production of willow in short rotation forests on agricultural land is also expected to cause low nitrogen losses, and this assumption is supported by measurements of low concentrations of nitrate and ammonium below the root zone of established willow crops.[5] Accordingly, willow production can fulfil the dual purpose of reducing nitrogen losses to waters and producing biomass for energy as planned in "The Danish government's action plan for energy 1996: Energy 21".[6]

If willow production is to be a tool in land use planning, there is, however, a need to increase our knowledge of nitrogen losses as affected by soil type, fertilisation, etc. Furthermore, data are not available to describe what happens during the establishment period, when forestation can cause significant losses on fertile agricultural land.[4] Therefore, these aspects are currently being investigated at two sites in Jutland in

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Denmark, and the results from the first three years after planting are presented here.

2. MATERIALS AND METHODS

2.1. *Experimental plan*

The experimental areas were planted with willow (*Salix viminalis*) early May 1993 at two sites, a loamy sand at Foulumgård, Research Centre Foulum, and a sandy soil at Jyndevad Experimental Station, situated respectively in the middle of Jutland, 12 km east of Viborg and near the border between Denmark and Germany, 18 km east of Tønder. The plan for the experiments is set out in Table 1, which also shows the treatments where nitrate leaching was measured.

The willows were placed in double rows with an internal distance of 75 cm and a distance between the double rows of either 126 or 260 cm. The planting distance in the rows was 55 cm. Nitrate leaching was only measured in the treatment with large distance between the double rows.

Two Swedish clones, 78-112 and 78-183, were used at Foulum while at Jyndevad only the clone 78-112 was used.

The fertilized treatments were given 37.5 kg N, 10 kg P and 45 kg K per ha the first year and 75 kg N, 19 kg P and 56 kg K the following years. The fertilizer was given in a 2 m band covering the two double rows, such that only 60% of the area in the 75/260 cm row distance treatment was fertilized.

At each site the eight treatment combinations were randomized inside each of three blocks. The plot size was 12.1×13.2 m or nearly 160 m^2.

Irrigation at Jyndevad was applied evenly to the whole experiment in 1993, but only with 17 mm before the planting of willows. In 1994 a drip irrigation system was installed in the irrigated treatments with tubes at 20 cm intervals along each row. Irrigation was applied whenever a soil tension of more than 0.6 bar occurred. However, the soil tension measurements with tensiometers were not satisfactory due to the uneven distribution of drip irrigation water in the very coarse soil. Irrigation was therefore applied according to estimated demands in 1995.

Weeding was only carried out in 1993, at Foulum by harrowing several times followed by inter-row weeding in July and rotavation outside the double rows in August, and at Jyndevad by spraying with Gardoprim in May and later by inter-row weeding twice in June.

2.2. *Soil sampling*

Soil samples were taken in May 1993 shortly after planting the willows. The samples were taken by a soil auger down to a depth of 135 cm at Foulum and 100 cm at Jyndevad and divided into different layers for analysis. The difference in sampling depth for the two sites was due to differences in expected rooting depth in the two soils.

2.3. *Registration of the climatic conditions*

At both experimental sites temperature, global radiation and precipitation were registered on meteorological stations within 1 km of the site. Potential evapotranspiration was calculated from the global radiation and temperature by a modified Penman.[7]

Table 1. Outlines of the experimental plan with indication of factors and treatments included in the investigations of nitrogen leaching

Locality	Exp. factors	Treatments	Calculation of N-leaching
Foulum	Row distance	75/126 cm	No
		75/260 cm	Yes
	Fertilizer	Unfertilized	Yes
		Fertilized	Yes
	Clone	78-112	Yes*
	(*Salix viminalis*)	78-183	Yes*
Jyndevad	Row distance	75/126 cm	No
		75/260 cm	Yes
	Fertilizer	Unfertilized	Yes
		Fertilized	Yes
	Irrigation	No irrigation	Yes
		Irrig. At 0.6 bar	No

*Not separated in the results.

2.4. *Estimation of production of woody biomass and nitrogen uptake*

The annual production of woody material in stems and branches was estimated by harvest of willow plants during the winter period when no leaves were present. Eight plants evenly distributed in the four rows at each end of the net plot were harvested by cutting the stems 10 cm above ground. For determination of total yield the total number of stems was counted on the plot. Dry matter and nitrogen content were determined on samples from stems and branches cut to chips.

2.5. *Root sampling*

Root samples were taken by coring the soil with an auger of 3.5 cm diameter. From the isolated soil cores 10 cm-length samples were taken from selected depths. The soil particles were removed by washing with tap water and the isolated roots were spread evenly on a tray and inspected through a microscope equipped with a hair line. From the number of observed crossings of the roots with the hair line the total root length/cm^3 soil was calculated by using the Newmann[8] formula.

2.6. *Nitrate measurements*

Nitrate concentration was measured in the soil solution after isolation by ceramic suction cups.[9] The cups were placed in two horizontal positions: (1) in a position inside the double rows in the middle of the 75 cm distance and (2) in a position outside the double rows in the middle of the 260 cm distance. The last position was therefore 68 cm outside the fertilized band.

At Foulum the cups were placed at a depth of 1.7 m and 1.2 m for the inner and outer positions, respectively, while at Jyndevad all the suction cups were placed at a depth of 1.0 m. These depths were expected to ensure that only insignificant root development took place below the cups. In one of the replicates at Foulum the cups were placed in clone 78-183, but the two clones were not separated in the calculations of nitrate leaching and therefore three replicates are represented. The two clones are found to be rather equal in production of woody biomass according to our estimates and to Bergkvist *et al.*[10] Samples of soil solution were taken periodically, and in periods of high percolation once a week.

2.7. *Measurements of soil water content*

The water content of the soils was measured at the inner and outer horizontal positions corresponding to those for nitrate and usually on the same dates as removal of soil solution.

At Foulum the soil water content was measured with TDR (time domaine reflectometry)[11,12] with a probe length measuring the whole layer from 0 to 1 meter. The TDR-measurements started in July 1994 and the probes were placed only in the fertilized treatment and only in two replicates.

At Jyndevad the neutron moderation method was used with measurements at 10 cm intervals down to 100 cm. In 1993 only three tubes were installed in the inner position of the fertilized treatment. From 1994 neutron tubes were placed in both the inner and outer position in two of the replicates in both the unfertilized and fertilized treatments with no irrigation.

2.8. *Calculation of nitrate leaching*

The drainage percolation from the root zone was estimated according to the equation

$$A = P - E - \mathrm{d}W$$

where A = percolation, P = precipitation, E = evapotranspiration and W = change in the soil water content. This calculation was carried out for each period between two samplings of soil solution for nitrate determination.

The potential evapotranspiration was at first used as a value for E. If by using this value the calculated drainage for a period was negative the drainage was set to zero and the actual evapotranspiration could be calculated from $E = P - \mathrm{d}W$.

For willow it has been found[13] that if water content in the soil is high the actual evapotranspiration in July to October can be higher than the potential evapotranspiration with a factor varying from 1.2 to 1.6 for the midseason and up to 2 for the latest part of the period. In the present calculations the actual evapotranspiration was set at 1.5 times the potential evapotranspiration from July to October if the actual available soil water content was above 80% of the water holding capacity.

The nitrate-N leaching was calculated by multiplying the amount of drainage water for a period with the mean value of the nitrate-N

Table 2. Texture of the soils in different layers. Mean of samples from three blocks. Standard deviation (SD) is mean of all layers

		Fraction size and content in percentage weight*				
Locality	Depth (cm)	Clay (< 2 μm)	Silt (2–20 μm)	Coarse silt (20–63 μm)	Sand (63–200 μm)	Coarse sand (200–2000 μm)
Foulum	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
Jyndevad	0–20	5.6	4.1	1.0	14.5	72.1
	20–40	5.4	3.0	1.0	12.6	76.0
	40–60	4.9	1.9	1.0	12.1	78.9
	60–80	4.2	1.2	1.5	12.3	80.1
	SD	1.5	0.4	0.3	6.4	6.6

*Humus excluded from this table, see Table 4.

concentration measured at the beginning and the end of the period.[14] Nitrate leaching calculated on the basis of nitrate in soil solution from ceramic cups is found to agree well with measured leaching from lysimeters and leaching estimated from nitrate in soil cores.[15]

2.9. *Analyses*

The two soils were analysed for textural composition and content of exchangeable nutrients. The mineral fractions of the textural composition were determined by a combination of the hydrometer method using sedimentation in 0.1 M sodium pyrophosphate and sieving. Humus content was determined by the Ter Meulen method of combustion using a CNS analyser.[16] Exchangeable cations were extracted by 0.5 M ammonium acetate for Na, K and Mg, while Ca was extracted by 1 M ammonium chloride. Na and K were measured by flame photometry and Mg and Ca by atomic absorption spectrophotometry. Exchangeable P was extracted by 0.5 M sodium hydrogen carbonate and measured spectrophotometrically after reaction with ammoniummolybdate/ascorbic acid.[17]

Total nitrogen in the soils was determined by the Kjeldahl procedure and in the willow material by the Kjeldahl or the Dumas method.[18] Nitrate- and ammonium-N in the soils were determined on an autoanalyzer after extraction with 1 M KCl.

Nitrate in the soil solution was determined on an autoanalyzer after reduction to nitrite and reaction with sulphanilamide and N-(1-naphthyl)-ethylene diamine.[19]

3. RESULTS

3.1. *Soil conditions*

For both sites the largest part of the soil is sand with a particle size above 63 μm (Table 2) of which at Jyndevad the great majority is

Table 3. Soil pH and content of exchangeable mineral nutrients in May 1993. Standard deviation (SD) is mean of all layers

			Exchangeable minerals (mg/kg g dry soil)			
Locality	Depth (cm)	pH 0.01 M $CaCl_2$	P	K	Mg	Ca
Foulum	0–20	6.4	55	141	48	2180
	20–40	5.9	33	116	31	1660
	40–60	5.1	30	93	19	873
	60–100	4.5	33	90	20	447
	100–135	4.4	19	91	46	487
	SD	0.3	8	11	6	278
Jyndevad	0–20	5.6	47	63	28	867
	20–40	5.7	26	45	22	643
	40–60	5.2	16	28	11	290
	60–80	5.0	12	20	7	153
	SD	0.1	4	2	1	29

Table 4. Content of humus and total and mineral nitrogen in different layers of the two soils in May 1993. Standard deviation (SD) given as a range from the lowest to the highest content when the variation was high between layers

Locality	Depth (cm)	Humus (% of dry soil)	Total-N (g/kg dry soil)	NO3-N (mg/kg dry soil)	NH4-N (mg/kg dry soil)
Foulum	0–20	5.7	2.26	16.8	1.9
	20–40	4.5	1.52	7.7	0.7
	40–60	3.0	0.97	5.2	0.9
	60–100	1.1	0.43	4.2	0.9
	100–135	0.4	0.25	6.5	1.4
	SD	0.1–1.4	0.01–0.33	1.0–3.1	0.27
Jyndevad	0–20	2.7	1.12	8.8	1.7
	20–40	1.9	0.72	5.2	0.8
	40–60	1.1	0.45	2.3	0.5
	60–80	0.7	0.29	1.6	0.2
	SD	0.1–0.02	0.03–0.12	0.4–2.0	0.05–0.09

coarse sand ($>200\ \mu$m). The clay and silt fractions ($<63\ \mu$m) are somewhat higher at Foulum amounting to 33–39% compared with only 7–11% at Jyndevad. The contents of exchangeable minerals are also higher at Foulum (Table 3) than at Jyndevad, where they are especially low below 60 cm.

The contents of humus and total nitrogen (Table 4) are considerably higher at Foulum than at Jyndevad, and the humus content is also high at Foulum compared to normal Danish conditions for mineral soils.[20] The content of mineral nitrogen (NH_4- and NO_3-N) was high, amounting to 174 and 62 kg N/ha down to the investigated depths of 135 and 80 cm for Foulum and Jyndevad, respectively.

Plant available water content to 1 m depth is about 185 and 80 mm for the loamy sand and the coarse sand, respectively, according to previous measurement in the two soils.[21,22]

3.2. *Climatic conditions*

The climatic conditions for the summer and winter half-year periods during the three experimental years are given in Table 5 where the normal climatic conditions for the two sites are also shown. The climate in the winter periods is of most importance to the nitrate leaching. The winter half years October–March 1993–94 and 1994–95 were characterized by temperatures near to and above normal, respectively, while precipitation was considerably higher than normal. In the winter 1995–96 the temperature was lower than normal and was below zero in the period December–March. Precipitation was much lower than normal.

Mean temperature and precipitation were for all periods higher at Jyndevad than at Foulum in agreement with normal values for the sites.

3.3. *Production of woody biomass and concentration of nitrogen*

The annual production of woody dry matter increased from year to year except in 1995 at Jyndevad compared to 1994 (Table 6). Application of fertilizer only increased the yield significantly at Foulum in 1994.

The concentration of nitrogen in the wood was lower at Jyndevad than at Foulum and decreased from year to year (Table 6). N-fertilization had no effect on the nitrogen content in wood.

Table 5. Climatic conditions for half year periods and the normal for 1961–90

	Foulum		Jyndevad	
Period	Precipitation (mm)	Mean temperature (°C)	Precipitation (mm)	Mean temperature (°C)
Apr 93–Sep 93	393	11.5	436	12.5
Oct 93–Mar 94	418	2.1	627	3.0
Apr 94–Sep 94	454	12.7	509	13.6
Oct 94–Mar 95	458	3.7	702	4.4
Apr 95–Sep 95	287	12.6	371	13.4
Oct 95–Mar 96	121	0.7	246	1.5
Normal Apr–Sep	362	12.1	456	12.7
Normal Oct–Mar	330	2.4	498	3.4

Table 6. Dry matter production and nitrogen concentration in woody part (stems and branches). Mean of the treatments on the 75/260 cm planting distance. Yield estimated by sampling eight plants/plot during the winter

		Dry matter yield of wood per year (*t*DM/ha)			Nitrogen concentration in wood (% N in DM)		
Locality	Year	0 N	75 N	SED*	0 N	75 N	SED*
Foulum	1993	1.25	1.32	0.13	1.27	1.15	0.11
	1994	2.68	3.71	0.37	0.75	0.74	0.05
	1995	8.71	6.93	1.26	0.70	0.67	0.05
Jyndevad	1993	1.62	1.64	0.20	0.81	0.82	0.02
	1994	3.52	4.94	0.90	0.55	0.57	0.04
	1995	3.67	3.61	1.47	0.54	0.51	0.03

*Standard error of difference.

3.4. *Depth of root development*

The measurement of roots was somewhat variable. However, the best estimate of rooting depth with a root density of at least 0.1 cm root/cm^3 soil is given in Table 7.

The roots were deeper inside than outside the double row and considerably deeper in the loamy sand than in the coarse sand. At Foulum the roots inside the double rows went deeper than the 1 meter for the water content measurement by TDR, while the roots did not reach this level at Jyndevad. No roots went down to the level of isolation of the soil solution for the nitrate measurement.

3.5. *Nitrate-N concentration in soil solution and amount of percolation*

At both sites the nitrate-N concentration increased during the autumn of 1993, reaching a rather high level especially at Jyndevad (Fig. 1). During the following winter the nitrate concentrations decreased at both sites, but to a different extent. At Jyndevad the concentration fell sharply during the first winter period to a constant level near zero, which was held for the next two years, while the decrease in nitrate-N concentration was rather slow at Foulum continuing through all three years.

At Foulum the nitrate concentration rose to a higher level outside than inside the double rows during the first autumn, but later the concentration was at a lower level outside the rows. At Jyndevad the nitrate concentration reached the highest level inside the double rows, but only where fertilizer was applied.

Percolation (Fig. 1, mean of fertilizer levels and positions) was high during the autumn–winter period 1993–94 and 1994–95, while it was very low for 1995–96 with no percolation at all at Foulum (Table 8). The mean percolation for the yearly periods is summed in Table 8. Effects of fertilizer levels and position cannot be determined for 1993–94. For the last two years the position effect for Foulum was very small, with only a 4 mm increase for the outside position. For Jyndevad, as a mean of the two years, the fertilized treatment (inside position) had 17 mm less and the outside position 17 mm more percolation than the unfertilized treatment (inside position).

3.6. *Calculated leaching of nitrate-N*

The leaching of nitrate was calculated according to treatment and the horizontal placement of the ceramic cups and summed for periods covering April to March the following year. Leaching was very high in the first period for both sites (Table 8). In the second period leaching was still appreciably high at Foulum inside the double rows, but low at Jyndevad. In the third period no leaching occurred at Foulum due to lack of percolation of water.

At Foulum the horizontal position of the ceramic cups did not significantly influence leaching in 1993–94 while in 1994–95 leaching

Table 7. Depth of root zone development given as the depth with a root density of 0.1 cm root/cm^3 soil

Site	Time	Inside double rows	Outside double rows
Foulum	Winter 1993–94	115	90
	Winter 1994–95	125	90
Jyndevad	Winter 1993–94	65	50
	Winter 1994–95	95	65

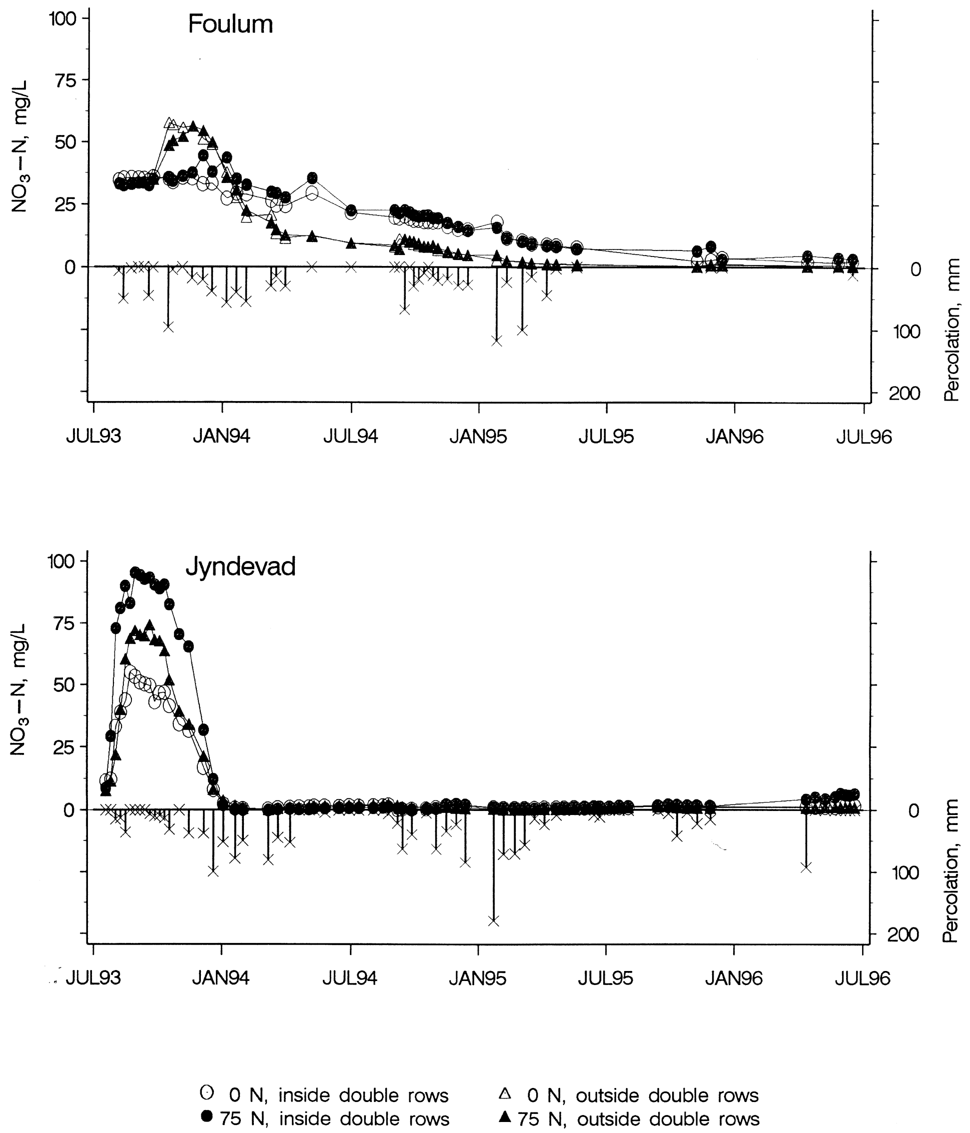

Fig. 1. Nitrate concentrations in soil solution and percolation of water during a three-year period of willow establishment.

was highest inside the double rows. There was no significant effect of fertilization.

At Jyndevad leaching in 1993–94 was significantly increased by fertilizer application, while in the second and third periods no or only a negligible effect of fertilizing can be seen.

3.7. *Nitrogen balance*

The nitrogen balance in kg N per ha was calculated taking into account the fertilizer nitrogen, nitrogen accumulated in above-ground wood and the leaching (Table 9). The leaching value is weighted according to the fertilized area (60%) covering the double rows and the unfertilized area (40%) outside the double rows. At Jyndevad leaching outside double rows was only measured for the fertilized treatment. It was, however, used in calculations for the unfertilized treatment as the outside position is outside the fertilized area and also no difference was found in the leaching from the unfertilized and fertilized treatment outside double rows on the loamy sand at Foulum.

Due to the large level of leaching in 1993–94 a large negative balance occurred. The balance for the second and third periods was still negative when no fertilizer was applied. In fer-

Table 8. Leaching of nitrogen in relation to site (soil type), year and fertilization

		Leaching of nitrogen (g NO3-N/m^2)					Percolation
		Inside double rows		Outside double rows			
Site	Period	–N	+N	–N	+N*	SD	Mean of treatments (mm)
Foulum	1993–94	12.6	14.6	15.1	14.8	1.2	404
	1994–95	8.2	8.5	2.7	2.9	3.2	537
	1995–96	0	0	0	0	—	0
Jyndevad	1993–94	9.4	18.3	—	11.6	2.2	669
	1994–95	0.7	0.8	—	0.7	0.3	780
	1995–96	0.2	0.4	—	0.2	0.1	209

*Outside fertilizer band.

tilized treatments the balance became positive at Jyndevad in the second period, but at Foulum only in the third period.

4. DISCUSSION

The experimental fields were agricultural soils with a high nutrient content, and mineralized nitrogen at the time of planting amounted to 174 and 62 kg/ha in the loamy sand and in the coarse sand, respectively. Even though the willow established well, only 13–16 kg N/ha accumulated in above-ground woody biomass during the first year. Consequently high amounts were leached during the first winter even without fertilizer application. However, leaching decreased dramatically on the coarse sand from the second season and on the loamy sand from the third season. A similar high level of leaching is observed when establishing forest on former agricultural land,[4] but with the leaching continuing over more years.

The leaching of N in the first period is at the upper level of leaching rates found for Danish soils in conventional agricultural production. Measurements at five Danish localities over a 20-year period[23] yielded a mean yearly rate of leaching of 58 kg N/ha varying from zero to 150 kg N/ha, while a later investigation at 13 localities over six years[24] gave a mean yearly leaching of 66 kg N/ha varying from zero to 237 kg N/ha. Of the 78 measurements, 14 had a yearly leaching rate above 100 kg N/ha.

No exact reason for the high content of soil mineral nitrogen at the start of the experiment in 1993 and the following high leaching has been found, but the growing season in 1992 was exceptionally dry[25] with poor crop growth, which can have caused residual nitrogen to be left over to 1993.

Application of fertilizer in the year of establishment did not increase productivity but increased nitrogen leaching on the coarse sand. Accordingly, fertilization should not be applied until the second year which is in accordance with Swedish recommendations.[26] From the second season no significant effect of fertilizer application on nitrate leaching was observed, which indicates that willow can be produced at recommended fertilizer levels

Table 9. Nitrogen balance in relation to site (soil type), year and fertilization

			Yearly N-balance (kg N/ha)			
Site	Period and fertilization		In fertilizer	Accumulated in wood	Leached	N-balance
Foulum	1993–94	–	0	–16	–136	–152
		+	38	–15	–147	–124
	1994–95	–	0	–13	–60	–73
		+	75	–22	–62	–9
	1995–96	–	0	–58	—	–58
		+	75	–44	—	+31
Jyndevad	1993–94	–	0	–13	–103	–116
		+	38	–13	–156	–131
	1994–95	–	0	–16	–8	–24
		+	75	–23	–9	+43
	1995–96	–	0	–19	–3	–22
		+	75	–16	–4	+55

without increasing leaching. This is supported by measurements in other young stands of willow,[5,27] but needs to be investigated in old stands as well, as here another nitrogen equilibrium may be reached.

The calculated nitrogen balance does not take into account atmospheric nitrogen deposition, mineralization, denitrification or ammonia volatilization. However, as the soil is sandy and as a mineral fertilizer was applied only the deposition value is expected to have a significant influence on the balance.[24] Atmospheric deposition under Danish conditions is expected to be 10–20 kg N/ha annually.[28,29] Accordingly the calculated balance is expected to be a measure of the change of soil N-content with a possible small addition from deposition. Initially the balance is very negative as the high mineral N-content at the beginning of the experiment was leached. When no fertilizer was applied, the crop utilized soil nitrogen reserves and the balance was negative during the whole experimental period. However, in fertilized treatments the balance turned positive after 1–2 years indicating a build-up of soil N. As soil nitrate concentrations were very low even in fertilized treatments, the accumulated N can be expected to be bound to carbon in organic substances. Accordingly, the data indicate that organic substances accumulate in fertilized willow except during the initial establishment period. An increase in soil carbon is a general observation in perennial crops irrespective of whether they are grass pastures[30] or short rotation woody crops.[31]

The experiment involved the investigation of water balance and productivity effects at two different distances between double rows. In this paper the effects of distance to the rows on nitrate leaching are reported. Roots developed during the year of establishment spread all over the area, even at the large distance of 260 cm between double rows. However, roots penetrated to a greater depth inside double rows than outside. The increased nitrate-N concentrations outside double rows in the unfertilised treatment at Foulum in the autumn of the first year could be caused by the shallower root development compared to inside double rows. However, the rise is more likely explained by a rotary cultivator treatment against weeds outside the double rows in late August only. Soil cultivation is known to increase mineralization.[32] The lower nitrate concentration outside than inside double rows during 1994 and 1995 is probably due to a smaller amount of organic nitrogen available for mineralisation. After 1–2 years no difference was observed between the inside and outside double row position, and it is assumed that the general conclusions on nitrate leaching are valid for normal distance between double rows as well.

The low nitrate-N concentrations measured after 1–2 years of establishment are well below the EU-limit for drinking water at 11.3 mg/l nitrate-N. The annual leaching in the last year was less than 10 kg/ha, and this would also have been the case at Foulum in 1995–96 due to the low concentrations even if normal percolation had occurred. These low levels of leaching are in accordance with earlier less detailed measurements in willow,[5,27] and similar low levels have been recorded from Miscanthus fertilized with 75 kg N/ha.[33] As the mean leaching from Danish agriculture on sandy soils is estimated to be about 100 kg N/ha (Jensen *et al.*, 1994) the change of land use into a willow or other perennial industrial crop can contribute a substantial decrease in leaching.[33] This is the case even if a high level of leaching during establishment is taken into account; when distributed over a 20-year rotation period it only contributed 5–10 kg N/ha annually. There is however a need to investigate methods of decreasing leaching during establishment. Possible methods could be no-till establishment or use of a catch crop between beds during the first couple of years.

REFERENCES

1. Danish Ministry of Environment, Action Plan on the Aquatic Environment, Copenhagen, 1987.
2. Simmelsgaard, S.E., The effect of crop, N-level, soil type and drainage on nitrate leaching, *Soil Use and Management*, 1998, **14,** 30–36.
3. Christensen, N., Jørgensen, F., Ernstsen, V. and Vinther, F.P., *Næringsstofomsætning i marginaliseret landbrugsjord (Nutrient flow in agricultural soils turned to be marginal)*. NPo-forskning fra Miljøstyrelsen, Report No. A13, 1-62. Danish Ministry of Environment and Energy, Copenhagen, 1990.
4. Callesen, I., Thormann, A., Rasmussen, K.R., Stryhn, H. and Østergaard, H.S., Nitrat-koncentrationen i jordvand under danske skove (Nitrate concentration in soil water below Danish forests), *Dansk Skovbrugs Tidskrift*, 1996, **81,** 73–93.
5. Nielsen, K.H., Virkning af slamgødskning på det omgivende miljø og på biomassekvantitet og -kvalitet i energiskove af pil (Effect of sludge application in willow energy platations on biomass quantity and quality and on environment), Ph.D. thesis, The Research

Series, No. 16, 111p, Danish Forest and Landscape Research Institute, Hørsholm, Denmark, 1996.

6. Danish Ministry of Environment Energy, Energy 21, The Danish Governments Plan for Energy, Copenhagen, 1996.
7. Mikkelsen, H.E. and Olesen, J.E., *Sammenligning af metoder til bestemmelse af potentiel vandfordampning (Comparison of methods for determination of potential evapotranspiration)*. Tidskrift for Planteavls Specialserie. Beretning No. S 2157, 1–67. Danish Institute of Agricultural Science, Tjele, Denmark, 1991.
8. Newmann, E.I., A method of estimating the total length of root in a sample, *J. Appl. Ecology*, 1966, **3,** 139–145.
9. Djurhuus, J. and Jacobsen, O.H., Comparison of ceramic suction cups and KCl extraktion for the determination of nitrate in soil, *Experimental Jorurnal of Soil Science*, 1995, **46,** 387–395.
10. Bergkvist, P., Nordh, N-E., Ledin, S. and Olsson, T., Plant material for short rotation forestry. In *Handbook on how to grow short rotation forest*, ed. S. Ledin and E. Willebrand. Swedish University of Agricultural Science, Uppsala, Sweden, 1996.
11. Jacobsen, O.H. and Schjønning, P., Comparison of TDR calibration functions for soil water determination. In *Proceeding of the symposium: Time Domaine Reflectrometry*, ed. L. W. Petersen and O. H. Jacobsen. Application in soil science. SP-report No. 11, 25–33. Danish Institute of Agricultural Science, Tjele, Denmark, 1995.
12. Thomsen, A., Manual and automated TDR measurements. In *Proceeding of the symposium: Time Domaine Reflectrometry*, ed. L. W. Petersen and O. H. Jacobsen. Application in soil science. SP-report No. 11, 39–43. Danish Institute of Agricultural Science, Tjele, Denmark, 1995.
13. Persson, G. and Lindroth, A., Simulating evaporation from short-rotation forest: variation within and between seasons, *Journal of Hydrology*, 1994, **156,** 31–45.
14. Lord, E.L. and Shepherd, M.A., Development in the use of porous ceramic cups for measuring nitrate leaching, *J. Soil Sci*., 1993, **44,** 435–449.
15. Webster, C.P., Sheperd, M.A., Goulding, K.W.T. and Lord, E., Comparisons of methods for measuring the leaching of mineral nitrogen from arable land, *J. Soil Sci*., 1993, **44,** 49–62.
16. Tabatabai, M.A. and Bremner, J.M., Use of Leco Automatic 70-Record Carbon Analyzer for total carbon analysis of soils, *Soil Sci. Amer. Proc*., 1970, **34,** 608–610.
17. Banderis, A., Barder, D.H. and Henderson, K., The use of polyacrylamide to replace carbon in the determination of "Olsen's" extractable phosphate in soil, *J. Soil Sci*., 1976, **27,** 71–74.
18. Hansen, B., Determination of Nitrogen as elementary N, an alternative to Kjeldahl, *Acta Agric. Scand*., 1989, **39,** 113–118.
19. Best, E.K., An automated method for determining nitrate nitrogen in soil extracts, *Queensland J. Agri. Animal Science*, 1976, **33,** 161–166.
20. Madsen, H.B. and Platou, S.W., Land use planning in Denmark: The use of soil physical data in irrigation planning, *Nordic Hydrology*, 1983, **14,** 267–276.
21. Andersen, A., *Rodvækst i forskellige jordtyper (Root growth in different soil types)*. Tidskrift for Planteavl. Beretning nr. S 1827, 90 pp. Danish Institute of Agricultural Science, Tjele, Denmark, 1986.
22. Jacobsen, O.H., *Umættet hydraulisk ledningsevne i nogle danske jorde (Unsaturated hydraulic conductivity for some Danish soils)*.. Tidskrift for Planteavl. Specialserie. Beretning nr. S 2030, 60 pp. Danish Institute of Agricultural Science, Tjele, Denmark, 1989.
23. Simmelsgaard, S.E., *Nitratkvælstof i drænvand 1971–91 (Nitrate nitrogen in subsurface drainage water in Denmark 1971–91)*. SP-rapport No. 47, 66 pp. Danish Institute of Agricultural Science, Tjele, Denmark, 1994.
24. Olsen, P., *Nitratudvaskning fra landbrugsjorde i relation til dyrkning, klima og jord (Nitrate leaching from arable land affected by management, climate and soil)*. SP-rapport No. 15, 86 pp. Danish Institute of Agricultural Science, Tjele, Denmark, 1995.
25. Olesen, J.E., *Jordbrugsmeteorologisk årsoversigt 1992 (Annual agrometeorological overview 1992)*. SP-report No. 10, 86 pp. Danish Institute of Agricultural Science, Tjele, Denmark, 1993.
26. Ledin, S. and Alriksson, A., Choice of site and establishing short rotaion forests. In *Handbook how to grow short rotation forests*, 2nd edn., ed. S. Ledin and E. Willebrand. Swedish University of Agricultural Scienece, Uppsala, Sweden, 1996, pp. 1–10.
27. Bergström, L. and Johansson, R., Influence of fertilized short-rotation forest plantations on nitrogen concentrations in groundwater, *Soil Use and Management*, 1992, **8,** 36–40.
28. Grundahl, L. and Hansen, J.G., *Atmosfærisk nedfald af næringssalte i Danmark (Atmospheric deposition of nutrient minerals in Denmark)*. NPo-forskning fra Miljøstyrelsen No. A6, 60 pp. Danish Ministry of Environment and Energy, Copenhagen, 1994.
29. Jensen, B.S., Stougaard, B. and Olsen, P., Simulation of water and nitrogen dynamics at three Danish locations by use of the DAISY model, *Acta Agric. Scand., Sect. B. Soil and Plant Sci*., 1994, **44,** 75–83.
30. Cuttle, S.P. and Scolefield, D., Management options to limit nitrate leaching from grass-land, *Journal of Contaminant Hydrology*, 1995, **20,** 299–312.
31. Hansen, E.A., Soil carbon sequestration beneath hybrid poplar plantations in the north central United States, *Biomass & Bioenergy*, 1993, **5,** 431–436.
32. Hansen, E.M. and Djurhuus, J., Nitrate leaching as influenced by soil tillage and catch crop, *Soil Tillage Research*, 1997, **41,** 203–219.
33. Jørgensen, U. and Mortensen, J., Perennial crops for fibre and energy use as a tool for fulfilling the Danish strategies on improving surface and ground water quality. In *Alternative use of agricultural land.* SP-report No. 18, 12–21. Danish Institute of Agricultural Science, Tjele, Denmark, 1997.