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The contribution of mineralization to grassland N uptake on peatland soils with anthropogenic A horizons

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Abstract Peatland soils contain large amounts of nitrogen (N) in the soil and mineralization can contribute substantially to the annual mineral N supply of grasslands. We investigated the contribution of N mineralization from peat with respect to the total annual N uptake on grasslands with anthropogenic A horizons and submerged tile drains. The study included i) a pot experiment to determine potential N mineralization from the topsoil and the subsoil, ii) a 1-year field experiment to study herbage yields and N uptake under fertilized and non-fertilized conditions and iii) a 3-year field study where herbage yield and N uptake from the top 30 cm and the entire soil profile were monitored. The 3-year field study yielded an average N uptake of 342 kg ha^{-1} under non-fertilized conditions but the contribution of subsoil peat N mineralization to the total N uptake was found to be negligible. Our calculations demonstrate that peat N mineralization contributed only 10% to 30% to the total N-uptake, mainly coming from the top 30 cm. Most of the N uptake under unfertilized conditions appears to be largely the result of mineralization from long-term inputs of dung, ditch sludge, farmyard manure, cow slurry and non-harvested herbage.

Keywords Peat soils · Anthropogenic A horizon · N mineralization · Grassland · Groundwater · Subsidence

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Introduction

Long-term agricultural use of peatland soils may result in drastic subsidence of the land surface (Kluge et al. 2008). Some peatland soils, such as those located in the lower reaches of the Rhine-Meuse Delta, contain large amounts of nitrogen (N) and peat decomposition is a substantial contributor to the mineral N supply of crops. As a consequence, annual N supplies of these lowland peatland soils are relatively high as compared to mineral soils. For non-fertilized poorly drained peat grasslands in The Netherlands, an average N uptake of 252 kg ha^{-1} was found, based on 60 years of experiments (Vellinga and André 1999). Van Kekum (2004) reported annual N uptakes from unfertilized experimental fields on peatland soils in the Western part of the Netherlands that ranged from 176 kg N ha^{-1} for wet peatland soils to 302 kg N ha^{-1} for drained peatland soils. Schothorst (1977) even reported annual N uptakes from non-fertilized peatland soils exceeding 400 kg N ha^{-1}. Generally, drainage of peatland soils results in a strong

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increase in the annual N supply (Hacin et al. 2001; Renger et al. 2002), which is most apparent in the first years after the start of drainage. Apart from N uptake, nitrous oxide emissions through denitrification are also considered to be a major pathway of N removal from intensively managed grasslands on peat soil (Regina et al. 2004; Van Beek et al. 2004).

On peatland soils (Terric Histosols) along the old Rhine river in the west of the Netherlands, anthropogenic topsoils have been formed through additions of sludge from ditches, city wastes and animal manure and are between 20–50 cm thick (Van Egmond 1971; Van Wallenburg and Markus 1971). Additionally, these topsoils ('toemaak' in Dutch) contain large amounts of dune sand which was used as bedding material in the stables (De Bakker 1982). As a result, particle size distributions indicate that the fraction >150 µm varies between 20% and 40% in peat soils with anthropogenic A horizons, whereas for peat soils in other parts of the country, the fraction >150 µm is less than 10% (Van Wallenburg and Markus 1971). These anthropogenically modified topsoils therefore have higher bulk densities and an improved soil structure (Van Egmond 1971). With this, the bearing capacity, which is normally low on these peat soils (Van Wijk 1988), is also improved. This reduces the risk of soil structure deterioration as a result of cattle trampling in pastures. These topsoils have also been found to contain elevated levels of lead, copper and zinc (Rutgers 2008). According to the Dutch soil map, almost 20,000 ha of peat soils have such anthropogenic topsoil predominantly in the Western part of the Netherlands in the provinces of South Holland and Utrecht. Many of these raised peat soils contain wood-sedge peat in the subsoil (*Carex* spp. and *Alnus* spp.) (Schothorst 1977, 1982).

Though currently the practice of adding dune sand and city wastes to peatland soils has disappeared, land spreading of sludge from ditches and the application of farmyard manure are still being practiced in parts of these peat areas. Manures can supply N beyond the year of application, resulting in so-called residual effects (Schröder et al. 2005). This is caused by the fact that the complete decomposition of organic inputs generally takes many years. In addition, N from atmospheric deposition, biological fixation by leguminous plant species and N release from unharvested herbage returned to the soil also contribute to the total soil N supply. In fields with long intensive manuring histories, there are thus multiple potential N sources that contribute to the annual N uptake of grassland under non-fertilized conditions. The peat itself therefore contributes partly to the total N uptake, whilst the remainder will be the result of other sources, including historic additions of ditch sludge, animal slurry, farmyard manure and dung.

The objective of the present study is to investigate the contribution of N mineralization from peat to the total annual N uptake by grass on lowland peatland soils, characterized by relatively low C/N ratios, with anthropogenic A horizons. Results from our investigation may contribute to the environmental evaluation of grasslands on drained peatland soils.

Materials and methods

The research was performed on a commercial dairy farm in the Western peat district of the Netherlands (Fig. 1) for which it was known that anthropogenic topsoils occurred (Sonneveld et al. 2008). For the greater part the farm consists of grasslands on Terric Histosols. The total thickness of the peat here is about 8 m (Hudig and Duyverman 1950). All fields are drained with submerged drains at 60 cm below the surface. The groundwater level fluctuates approximately between 20 and 60 cm below the surface in the winter and the summer respectively. Ditch water levels are kept between 40 and 60 cm below the land surface throughout the year (De Vos et al. 2008). All fields surrounding the farm have a long (>50 years) history of fertilization with ditch sludge, farmyard manure and slurry.

Three experiments were included in this study: experiment 1 was a pot experiment and experiments 2 and 3 were field experiments. Experiment 1 was carried out in 2005 with the aim to determine the potential subsoil N mineralization rate compared to that from the predominantly anthropogenic top layer. Four pots were filled with homogenized soil from the top layer (0–20 cm) and four pots with soil from the layer beneath (20–40 cm). Each pot (surface area 0.876 m^2) contained 0.0165 m^3 soil. Grass was sown in March 2005 and the pots were regularly irrigated during dry periods. Fertilization with K (150 kg K_2O ha^{-1}) and P (100 kg P_2O_5 ha^{-1}) was done in the beginning of the growing season to prevent possible deficiencies. The grass was harvested three times in 2005 (20 June,

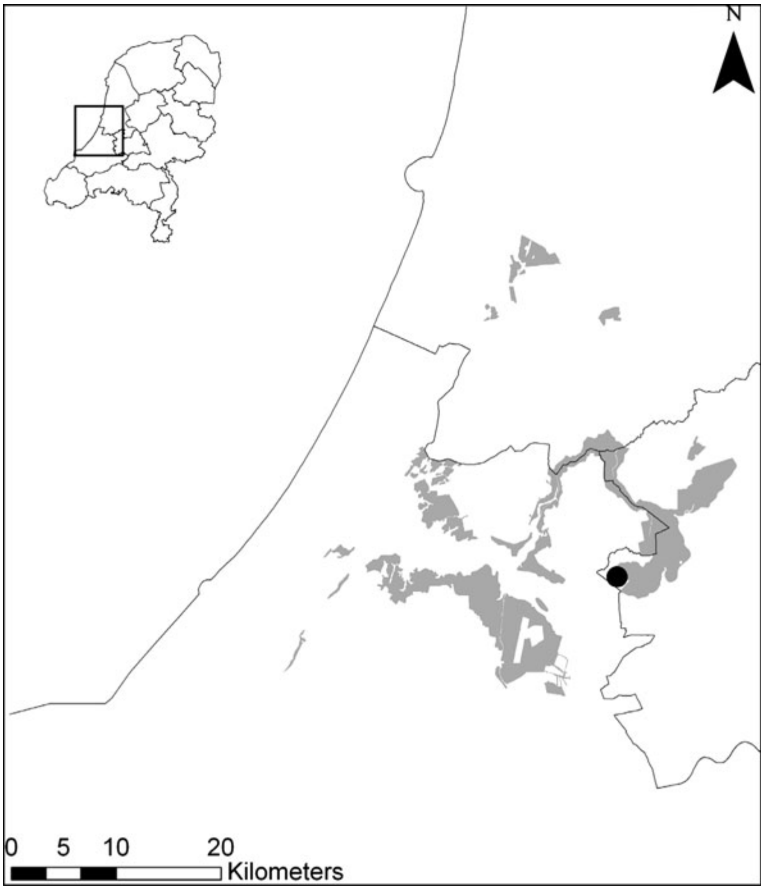

Fig. 1 Distribution of anthropogenic topsoils on peatland soils in The Netherlands and location of the farm (*black circle*). Administrative boundaries of provinces are indicated

8 August and 5 October) and dried (70°C) to determine dry matter (DM) and N contents (Skalar Segmented Flow Analyzer).

Experiment 2 was also conducted in 2005 and took place on four grassland fields close to the farm buildings. The aim was to study the first-year contribution of organic N inputs to total N uptake. In each field two grass cages of 4.50×1.25 m (Lantinga et al. 2004) were placed of which the sward area of one cage received applications of slurry, partly composted farmyard manure and ditch slurry throughout the growing season by the farmer according to his normal practice. The other cage area was kept unfertilized by covering the cage with a sheet during fertilization events. Hence, four cages received manure and four cages were kept unfertilized. Application of slurry started on 10 March 2005, whereas farmyard manure was not applied before mid-June. On the total area of the four fields (9.7 ha), 74 tanks of 6.1 m^3 slurry with a mean N content of 3.7 kg N per m^3 were broadcasted (final application date 9 September 2005). By far the greater part of the slurry (75%) was applied before mid-July, since in late summer N-fixing white clover flourishes on this farm in the pastures. Total amount of applied farmyard manure on the four fields was 168 Mg (on average 7 kg N per Mg), rather evenly distributed between mid-June and mid-September. Total N application rates with slurry and farmyard manure were aggregated cumulatively over four periods of the growing season, coinciding with four of the cutting dates (19 May, 11 July, 7 September and 17 October).

Herbage yields above a stubble height of 4 cm were measured at regular intervals by using a motorized mower (Lantinga et al. 2004), and dry matter (DM) and N contents of subsamples were determined using a Skalar Segmented Flow Analyzer after drying these at 70°C. Bookkeeping data from the farmer from previous years with respect to fertilization were collected. Bulk density measurements were done with 300 cc cores on the same field and the samples were dried at 105°C. Soil organic matter (SOM) contents were determined after drying at 105°C and oxidation at 900°C. Particle size distributions were determined using laser diffractometry (Coulter LS 230).

Experiment 3 was a 3-year (2006–2008) field study, which was initiated to study the N uptake and dry matter production from the topsoil (in this case the 0–30 cm layer) and the subsoil separately under non-fertilized conditions. In this study, again grass cages were used. In 2006, four cages were installed on a field (field III) close to the farm buildings and within each cage two treatments were imposed. Treatment 3.1 was an undisturbed 'control' subplot of 60×60 cm. Treatment 3.2 consisted of a subplot of 60×60 cm where the topsoil of 30 cm was manually lifted as a whole and a root cloth was put between this block and the subsurface and along its sides. This prevented the roots from penetrating into the subsoil. The block of soil was then re-positioned on top of the subsoil. In February 2007, the soil beneath two of the cages was visually inspected to see whether the roots had penetrated the root cloth which was not the case. Four cages were added to the experiment in spring 2007 on a neighboring field (field IV) where in each cage treatments 3.1 and 3.2 were repeated and an extra treatment (3.3) was added to observe the effect of the sward disturbance itself on N mineralization and dry matter production. For this purpose, a block of 60×60 cm topsoil (30 cm depth) was lifted and re-positioned without placing a root cloth underneath.

The herbage was harvested at regular intervals with a spinach knife using a metallic frame (50×50 cm) with attached pins (Lantinga et al. 2004) to ensure a constant cutting height of 4 cm. The samples were dried, weighed and analyzed for N content. For both fields, soil samples were taken at two depths around the cages (0–30 cm and 30–60 cm) in autumn 2008, bulked and analyzed for soil texture and C and N contents using near infrared spectrometry. Farm slurry and farmyard manure samples were taken regularly for analysis in all years. In June 2009, four ditch sludge samples were captured in open pans during field application and analyzed. In order to obtain more detailed information of groundwater level fluctuations during experiment 3, automatic groundwater level recordings at 15 min intervals were taken on Field IV from the summer 2007 onwards.

Data from all three experiments were analysed using PASW statistics (SPSS inc.).

Results

Experiment 1. Pot experiment 2005

Soil N content of the top 0–20 cm was higher (17 $g kg^{-1}$) compared with the lower 20–40 cm layer (13 $g kg^{-1}$). Total aboveground N uptake of the herbage grown on the topsoil was slightly more than four times higher (244 kg N ha^{-1}) than that from the subsoil (59 kg N ha^{-1}). However, the fractional soil N uptake, relative to the total soil N content, differed less due to a lower soil N content in the subsoil layer (1.43% vs. 0.45%). Thus, the potential N mineralization rate from the decomposed peat subsoil can be estimated up to four times lower than that from the topsoil. Note that the growth period of the herbage in this pot experiment (sowing data 22 March 2005) was about 2 months shorter than in the field experiment of 2005 (experiment 2). This reduced the total N uptake over the growing season, possibly by a third.

Experiment 2. Field experiment 2005: N supply from manure and ditch sludge and N uptake

Some soil properties of field III are given in Table 1. Clay contents were lower in the topsoil compared with the subsoil, as was also found by De Bakker (1982) for a similar soil profile. SOM contents were highest in the topsoil (39%) and decreased slightly with depth. The bulk density of the top 20 cm was almost twice as high (0.59 $g cm^{-3}$) compared to the bulk density of the 45–55 cm layer (0.30 $g cm^{-3}$). The fraction >150 μm in the top 20 cm was 25%, indicating the presence of an anthropogenic topsoil with mineral elements. The presence of roots was mainly confined to the topsoil and was very low below 45 cm.

The main results of the field experiment are presented in Fig. 2 as cumulative amounts on four dates of the growing season. According to a stepwise regression analysis there appeared to be non-significant differences between the calculated herbage N recovery values of applied slurry and farmyard manure throughout the year. Therefore, the data for

Table 1 Selected soil properties of field III where field experiments were conducted. Data shown are single observations

Depth (cm)	Soil description	Texture (%) Clay %<2 μm	Clay+Silt %<50 μm	Sand %>150 μm	SOM[b] %	BD[c] (gcm^{-3})
0–20	Very dark grey (10YR 3/1)[a], with anthropogenic artifacts of glass and pottery, with sand grains	27	66	25	39	0.59
20–45	Black (10 YR 2/1), decomposed wood-sedge peat	42	76	19	37	0.45
45–55	Black (10 YR 2/1), non-decomposed wood-sedge peat	nd[d]	nd	nd	34	0.30

[a] Munsell colour chart

[b] Soil Organic Matter

[c] Bulk Density

[d] nd = not determined

the two manure types were aggregated and a multiple linear regression analysis revealed:

$$Nuptake\left(kg\ N\ ha^{-1}\ yr^{-1}\right) = 0.54(\pm 0.02)*manure\ N + 0.21(\pm 0.12)*sludge\ N\left(R^2 = 0.997\right) \quad (1)$$

The mean manure apparent N recovery by the aboveground herbage of 0.54 had only a small standard error (0.02), whereas the 95% confidence interval of that for ditch sludge N recovery was large and varied between −0.04 and 0.46 (mean 0.21). Ignoring this non-significant contribution of N uptake from ditch sludge, it follows that at the end of the growing season the total N recovery from the two manure sources was 0.60.

The total annual amount of applied N from the two sources that contributed to N uptake was 288 kg N ha^{-1} of which only 80 $kgha^{-1}$ was mineral N. Based on previous ammonia volatilization measurements on this farm (Sonneveld et al. 2008), a volatilization loss of about 20 kg N $ha^{-1}yr^{-1}$ might be assumed (i.e. 0.25 of the applied mineral N) whereas the remainder (60 kg N $ha^{-1}yr^{-1}$) is considered to be taken up in the first year, ignoring field N losses through nitrate leaching (Sonneveld et al. 2008). In the experimental plots, the measured herbage N uptake equaled 172 kg N $ha^{-1}yr^{-1}$ (Fig. 2) of which 112 kg N $ha^{-1}yr^{-1}$ is considered to be the result of the first-year mineralization of applied organic N. Consequently, the first-year recovery of applied *organic* N can be calculated at 0.54. This value will be used in the analysis of

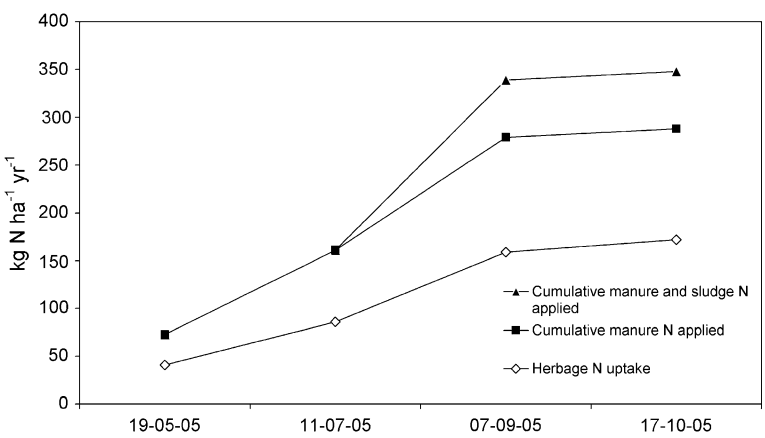

Fig. 2 Cumulative animal manure N supply (■), total animal manure and ditch sludge N supply (▲) and herbage N uptake (-) in the field experiment of 2005

experiment 3 to calculate the contribution of manure N to mineralization.

Experiment 3. Field experiments 2006–2008: dry matter yield and N uptake from non-fertilized plots

Soil properties for fields III and IV are given in Table 2. For field IV, it was found that total N content and SOM content of the 30–60 cm layer were higher compared with the 0–30 cm layer which was in contrast with field III. This reflects the heterogeneity of these fields due to past anthropogenic activities. In agreement with earlier observations by De Vos et al. (2008), groundwater levels during the experiment fluctuated only slightly between 30 and 60 cm (Fig. 3). In autumn 2008, several plots were substantially damaged by boroughs of rodents (5%–25% damaged area) and the grassland yields were corrected accordingly.

Results for total annual N uptake by the grassland for 2006, 2007 and 2008 are given in Fig. 4. Mean values ranged from 283 kg N ha^{-1} to 480 kg N ha^{-1}. Total N uptake was always consistently lower for the control plot (treatment 3.1) compared with the other treatments. The differences between treatments 3.2 (root cloth at 30 cm) and 3.1 became small after 3 years in field III. In this field, differences between the means decreased gradually from 70 kg N ha^{-1} in 2006 via 30 kg N ha^{-1} in 2007 to 18 kg N ha^{-1} in 2008. However, the difference increased from 74 kg N ha^{-1} in 2007 to 132 kg N ha^{-1} in 2008 in field IV, but this was accompanied by increased standard error values (Fig. 4). When examined for both fields and for all 3 years together, treatment 3.2 was significantly higher compared to treatment 3.1 (70 kg N ha^{-1}, $P<0.05$). Averaged over 2007 and 2008, treatment 3.3 (lifted topsoil) was significantly higher compared to treatment 3.1 (90 kg N ha^{-1}, $P<0.05$). Differences between treatments 3.2 and 3.3 in field IV were not consistent. In 2007, treatment 3.2 yielded a mean N uptake of 409 kg N ha^{-1} which was 30 kg N ha^{-1} lower compared to treatment 3.3. In 2008, treatment 3.2 yielded a mean N uptake of 480 kg N ha^{-1} which was 56 kg N ha^{-1} higher compared with treatment 3.3. Despite this, the differences between treatments 3.2 (root cloth at 30 cm) and 3.3 (lifted topsoil) were not significant for both years.

Consequently, disturbance alone following from treatments 3.2 and 3.3 yielded on average 70 kg N ha^{-1} and 90 kg N ha^{-1} higher annual N supplies, respectively, compared with the control plots (treatment 3.1). As results from treatment 3.2 indicated that limiting rooting depth to 30 cm did not result in reduced N yields, it follows that subsoil (>30 cm deep) contribution to the total herbage N uptake is minimal.

Estimating N mineralization from peat from the field experiments

There are various potential sources that contribute to the total annual N uptake from the unfertilized plots from the field experiments in experiment 3. These potential sources can be grouped into three categories. Category one involves external sources and includes biological N_2 fixation by leguminous crops and N from atmospheric deposition. Category two involves management sources and includes, next to unharvested herbage returned to the soil, mineralized N from previous applications of farmyard manure, slurry, sludge and dung. Category three involves mineralization from peat and includes both N from decomposing peat in the subsoil, which can be neglected in the current study, as well as N from decomposing peat that has been biologically mixed in the topsoil.

Net grassland N uptake can be formulated as follows:

$$N_u = \sum_{i}^{m} N_i \tag{2}$$

Where N_u is the total annual N uptake under non-fertilized conditions, N_i is the contribution of source *i*

Table 2 Soil properties per soil layer for fields III and IV as used in experiment 3. Data refer to analyses on mixed samples, based on eight individual samples

	Soil depth (cm)	Clay %<2 μm	Total N (gkg^{-1})	SOM (%)	C/N ratio
Field III	0–30	27	15.5	41	15
Field III	30–60	35	14.4	31	12
Field IV	0–30	29	12.0	29	14
Field IV	30–60	23	16.0	35	13

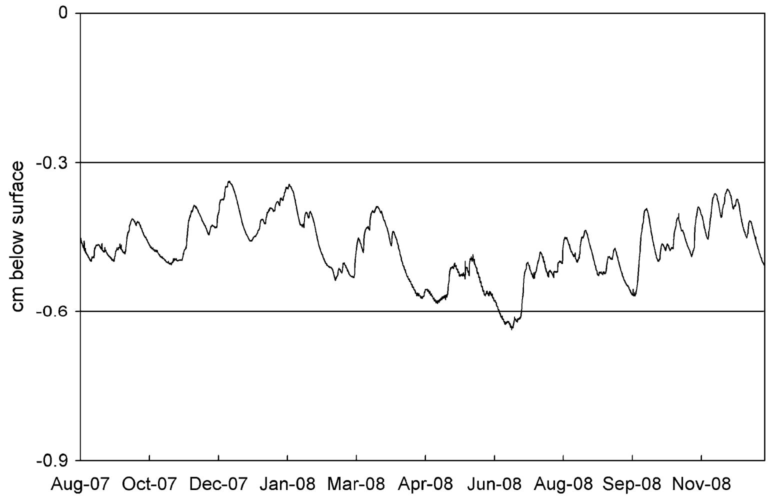

Fig. 3 Groundwater levels between the second half of 2007 and the end of 2008 in field IV

to the total annual N uptake and *m* the maximum number of sources. For the 3-year field experiment, it can be calculated from the data presented in Fig. 4 that the mean values for N uptake in the non-fertilized control plots (treatment 3.1) for fields III and IV were both 342 kg N $ha^{-1}yr^{-1}$ (N_u).

In our study, we assumed input levels with a variation of 10% or 20% for all sources N_i over the past 25 or 50 years. This means that we used uncertainty ranges of N input that deviated with 10% or 20% from the mean N input. Values for inputs are given in Table 3 and are explained below.

We estimated N inputs from fixation in this study at 0 kgha^{-1} because clover (*Trifolium repens* L.) was not observed in the non-fertilized control plots. The indigenous small-leaved white clover appeared to be not persistent under the cutting-only treatment in these plots. Furthermore, total N inputs from wet and dry deposition for this region are on average 31 kg N ha^{-1} (PBL 2008). However, this must be seen as the lower limit since almost 100% of the deposition from on-farm ammonia emissions (e.g. housing, storage and application losses) will take place within 300 m from the source (Sommer et al. 2009). Since the grass cages were placed in the proximity of the farm buildings and the very regular slurry applications took place up to the edges of the grass cages, we have increased this value. Therefore, for our calculations we used an average annual atmospheric deposition of 35 kg N ha^{-1} with a variation of 20%.

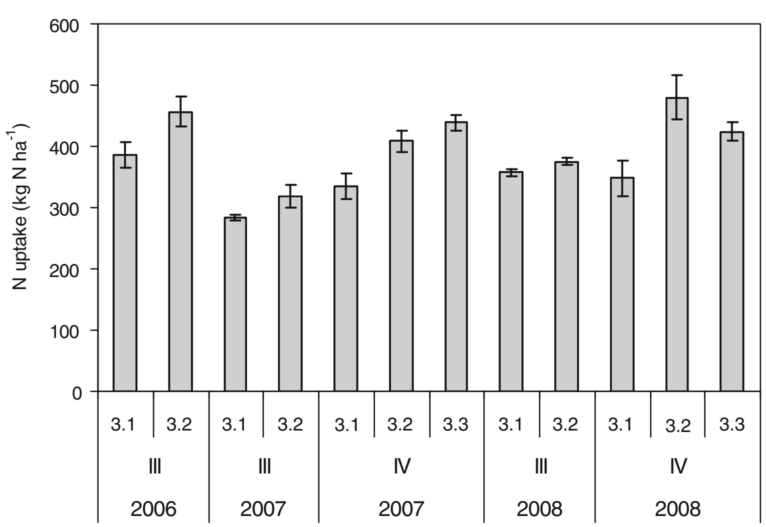

Fig. 4 Annual cumulative N uptake (kgNha^{-1}) by the grassland for the years 2006, 2007 and 2008 for the individual fields (III and IV) per treatment. Treatment 3.1 is the non-fertilized control plot, treatment 3.2 is the plot with root cloth at 30 cm and treatment 3.3 is the plot with the lifted topsoil (30 cm). Error bars indicate standard errors (*n*=4)

Table 3 Average annual inputs to fields III and IV under normal farm conditions (period 2004–2008) and the calculated range of residual organic N in the first year

Source	Input rate	Properties	N input	First year's N_{org} availability	Range in first year's residual N_{org}
	($ha^{-1} yr^{-1}$)		($kg ha^{-1} yr^{-1}$)	(%)	($kg ha^{-1}$).
Atmospheric deposition[b]		nd	35	100[c]	0
Unharvested herbage[b]		N_{org}:N_{tot}=1.0	120	60	38–58
Farmyard[a] manure	20 Mg	263 g DM[d] kg^{-1}, 7.0 g N_{tot} kg^{-1}, N_{org}:N_{tot}=0.9	140	54	52–64
Slurry[a]	50 m^3, bulk density 1,000 $kg m^{-3}$	92 g DM kg^{-1}, 3.7 g N_{tot} kg^{-1}, N_{org}:N_{tot}=0.6	185	54	46–56
Ditch sludge[b]	30 m^3, bulk density 1,000 $kg m^{-3}$	73 g DM kg^{-1}, 20 g N_{tot} kg^{-1} DM, N_{org}:N_{tot}=1.0	44	0	35–53
Dung[a]		N_{org}:N_{tot}=1.0	45	20	32–40
Total			569		203–271 (mean 237)

[a] input ±10%

[b] input ±20%

[c] N_{tot} (see text for explanation)

[d] Dry matter

Under normal farming practice with integrated grazing and cutting, part of the N uptake by grass is returned to the field because of death and decay losses from the sward layer between the experimental cutting height of 4 cm and the residual herbage above this height after a grazing cycle or a cutting event under normal farming practice. In 2005, which was a favorable grass production year, these losses were more than 7 Mg DM ha^{-1} (see experiment 2). For an average year we estimate them at 6 Mg DM ha^{-1} (with a variation of 20%) and a typical N content of 2% (Whitehead 1986). This results in a mean annual soil N input of 120 kg N ha^{-1}. However, the greater part of this (~60%) will already be mineralized in the first year, as can be derived from Janssen (1996). In the 3-year field study (experiment 3), mineralized N from this pool was harvested with the herbage above the 4 cm cutting height and should be corrected for.

Farmyard manure is applied on average in amounts of 20 Mg per ha per year. We measured a total N content of 7.0 $g kg^{-1}$ (~90% N_{org}). Cow slurry is applied at about 50 m^3 per ha per year and contained 3.7 g N kg^{-1}, most of which is in organic form (60%). For both manure types, we reckoned with the obtained first-year's availability of 0.54 for organic N (see experiment 2), indicating that 54% of the organic N will be mineralized in the year of application. Taking into account the ammonia volatilization, 25% of the mineral N (Sonneveld et al. 2008) during spreading, this yields a residual annual N input of 58 and 51 kg N ha^{-1} from applied farmyard manure and slurry, respectively. Variations from year to year are small because of rather constant animal numbers, so we assumed a variation of only 10% for these two inputs.

Ditch sludge has been applied on average every 2 years (not in wet summers) for more than 50 years. Application rates are difficult to estimate, but based on a measurement in June 2009 it was decided in collaboration with the farmer to assume an average annual application rate of 30 m^3 per ha with a variation of 20%. Sludge N samples had an average dry matter content of 73 $g kg^{-1}$ (~50% organic matter) and 20 g N per kg dry matter. We assumed an annual soil organic matter decomposition rate of 5% (B. Janssen, pers. comm.), starting only after the year of application. Due to the relatively high C/N-ratio of ditch sludge, net release of N will be retarded during the first months as a result of N immobilization (Van Strien et al. 1991). In the equilibrium situation, this results in an annual mineral N input of 44 kg N $ha^{-1}yr^{-1}$.

Finally, dung patches represent an N input source since the fields used for the current experiment are also grazed by cows under normal farming practice leading to N excretion through urine and dung. Based on the farmer's records (not shown) this results in an extra N addition of about 75 kg N $ha^{-1}yr^{-1}$ with a variation of 10%. Assuming a dung-derived organic N proportion of 60% in these excreta similar to that of slurry, i.e. a dung N addition of 45 kg N $ha^{-1}yr^{-1}$, and a first-year's N efficiency of 20%, the annual herbage N supply from dung remnants in the equilibrium situation can be calculated at 36 kg N ha^{-1}. Although the scarce data in the literature suggest that only about up to 10% of dung N is recovered by aboveground herbage in the year of deposition (Deenen and Van Middelkoop 1992; Jørgensen and Jensen 1997; Yamada et al. 2007), we have doubled this fraction to 20% in order to take into account the established high N recovery from the applied farmyard manure on this farm. This yields 36 kg N ha^{-1} yr^{-1}. Total residual amounts of organic N at the end of the grass growing season of an average year are 237 kg N ha^{-1} according to Table 3. After a 25 year period, almost all input sources N_i will be at equilibrium with mineralization, except for sludge. However, as noted before, average application rates of this input have not changed significantly during the last 50 years.

The annual contribution of N mineralization from peat in the top 30 cm can now be calculated as the herbage N uptake without fertilization minus equilibrium net N mineralization from all inputs and minus the herbage N uptake due to atmospheric deposition. This results in an average value of 70 kg N $ha^{-1}yr^{-1}$ for the contribution of peat mineralization from the top 30 cm to the total N uptake. Considering the variability in input rates (Table 3), a range of 30–110 kg N ha^{-1} is calculated. This implies that the relative contribution of peat decomposition to grassland N uptake ranges between approximately 10% and 30% and dominantly originates from the topsoil. The remaining grassland N uptake is largely the result of mineralization from organic N inputs from previous years involving dung, ditch sludge, farmyard manure, slurry and unharvested herbage.

Discussion

Considering the long intensive manuring history of the investigated fields of more than 50 years, the residual annual addition of organic N to the soil-N pool will act as a major contributor to the apparent soil N supply in the long term (Schröder 2005; Sluijsmans and Kolenbrander 1977). Although we did find high levels of N uptake, with a mean of 342 kg N ha^{-1} in the 3-year field experiment, the mean contribution of mineralization from the peat itself was calculated at 70 kg N ha^{-1} per year, mainly coming from the anthropogenic topsoil. This amount is lower than the values reported by Schothorst (1977). Groundwater level fluctuations in our case corresponded with groundwater level fluctuations reported by Schothorst (1977) for a field where the ditch water level was maintained at 25 cm below the surface. For this situation, Schothorst (1977) roughly estimated a soil N supply of 96 kg N $ha^{-1}yr^{-1}$. For ditch water levels at 70 and 80 cm below the surface, Schothorst (1977) calculated much higher soil N supplies from peat of 160 kg N $ha^{-1}yr^{-1}$ and 224 kg N $ha^{-1}yr^{-1}$ respectively. At this particular farm however, ditch water levels are never deeper than 60 cm below the surface (De Vos et al. 2008). Wessolek et al. (1999) observed over a period of 22 years an average net mineralization rate of 95 kg N $ha^{-1}yr^{-1}$ in the top 30 cm of a low moor peat soil in Germany with a groundwater level at 50 cm below the surface. The difference with our study might be explained by the lower peat content in the topsoil of our farm due to the past "toemaak" additions and the more recent anthropogenic applications of organic inputs. This is also in line with the results of the pot experiment where during one—not complete—growing season a net release of 59 kg N ha^{-1} from the subsoil (mixture of peat and "toemaak") was observed.

It is worth noting that the total herbage dry matter yield (DM) in the non-fertilized situation under the cages in experiment 2 was 14.9 Mg ha^{-1}, whereas in the plots fertilized with animal manure and ditch sludge this equaled 20.4 Mg ha^{-1}. According to the farm records, the net grassland yield in 2005 for the whole farm was 13.0 Mg DM ha^{-1}. The difference, i.e. about one third of the measured gross yield under the fertilized cages (=7.4/20.4), represents the herbage losses to be returned to the soil through death and decay (Whitehead 1986). They involve ungrazed herbage and field losses associated with making silage or hay from the sward layer above the experimental cutting height of 4 cm.

In our study, we did not account for peat N mineralization that is directly lost to the environment through denitrification. Koops et al. (1997) measured an average nitrous oxide production of 34 kg N $ha^{-1}yr^{-1}$ for incubated samples from non-fertilized grasslands on drained peatland soils. Regina et al. (2004) reported mean fluxes of N_2O of 4 to 7 kg N $ha^{-1}yr^{-1}$ for grasslands with mean groundwater tables at 82 and 42 cm below the surface and receiving annual N inputs through fertilization of more than 100 kg N $ha^{-1}yr^{-1}$. A mean denitrification rate of about 5 kg N $ha^{-1}yr^{-1}$ follows from Velthof et al. (1996) for field measurements on non-fertilized grassland plots on drained peatland soil. Hendriks et al. (2007) reported N_2O emissions from rewetted non-fertilized peatland soils that were close to zero. Although in this study we did not measure denitrification rates in the field in this study, it is possible that some N from peat mineralization may be directly lost to the atmosphere under non-fertilized conditions. However, we expect these losses to be small compared to the total annual N uptake. We neglected the input of N through capillary rise. The mean concentration of total N in the ground water for 2004 and 2005 was measured around 10 mg N l^{-1} (Sonneveld et al. 2008). As groundwater levels do not drop below 60 cm, capillary rise of 2 $mm d^{-1}$ can be maintained. For a growing period of 250 days, this would still result in negligible amounts that contributed to the input of N through capillary rise from the groundwater.

Although in our case we observed higher C/N ratios at greater depths, Wessolek et al. (1999) found that soil organic matter decomposition in peat soils results in a decrease of the C/N ratio. Additionally, these authors found that mineralization of N in the top 30 cm may coincide with immobilization in the lower 30–60 cm. Root density in our field was very low in one of the experimental fields below 45 cm depth (Table 1), but apparently as based on our observations from field experiment 3, N uptake from the soil below 30 cm depth is believed to be minimal. At maximum, the contribution of subsoil N mineralization may contribute to 7% of the total N uptake (field III, 2008).

We found that the total soil-N supply rates of drained lowland peatland soils was substantial with only approximately 20% (70 kg N $ha^{-1}yr^{-1}$/342 kg N $ha^{-1}yr^{-1}$) being contributed by N mineralization from peat. The particular farm studied uses submerged tile drains on its fields. In winter periods with a precipitation surplus, the tile drains result in a removal of water while in summer periods the tile drains result in infiltration of surface water because ditch water levels are higher than the depth of the tile drains. Interestingly, groundwater levels fluctuated within a very narrow range and groundwater hardly drops below the depth of the tiles (60 cm). Groundwater levels also did not reach the soil surface (Fig. 3). Thus, the range for groundwater-level fluctuations, 30 cm, was found to be relatively small compared to other studies in peatland soils (Van Beek et al. 2004).Without tile drains, groundwater in peatland soils may drop 30 to 50 cm below ditchwater levels (Schothorst 1977) resulting in an exposure of the non-decomposed peat to oxidized conditions. Given the fact here that subsurface peat layers are not periodically subjected to oxidized conditions, subsurface tile drains as applied here would potentially lower the risks for subsidence.

Drainage of peat soils results in mineralization, shrinkage and subsidence which also changes the bulk density. The observed bulk density of the topsoil in our study was found to be about twice as high compared with the 45–55 cm layer, a trend similar to the findings of Schothorst (1977) and Kluge et al. (2008). This higher bulk density closer to the soil surface will be partly due to shrinkage and partly due to the anthropogenic addition of solid sand size particles. An approximation of subsidence rates from mineralization may be obtained using the procedure described by Schothorst and Broekhuizen (1990). They also showed for the same area that shrinkage and oxidation dominantly takes place in the top 30 cm (87% of the total oxidation). Furthermore, Schothorst (1977) indicated that 85% of the total subsidence rate may be regarded as a result of peat decomposition, the remainder being mainly shrinkage. Taking the data from Table 2 for the top 30 cm with an N content of 15.5 $g kg^{-1}$ and a bulk density of 0.59 $g cm^{-3}$, the total subsidence rate, calculated from N mineralization of topsoil peat may be approximated at less than 2 mm per year. This estimate approaches the observations of Kluge et al. (2008) for extensively managed grasslands with shallow groundwater tables in East Germany. For recent decades, they reported a mean decrease in peat thickness of 2.7 $mmyr^{-1}$ for peatland soils with groundwater levels fluctuating between 50 and 70 cm below the surface. Wessolek et al. (1999) reported that about 70% of the total subsidence rate could be attributed to changes in the top 30 cm. Such findings indicate that our approximation at field scale may slightly underestimate actual subsidence rates which need validation through actual measurements. However, it should be noted that annual precipitation in East-Germany is lower and summers are drier compared with our study area. This may enhance N mineralization and subsidence. Estimations on subsidence rates at the larger regional scale will need to take account for spatial heterogeneity in historic land management practices and topsoil composition. Our calculations suggest that management on this farm, involving long term inputs of N through manure, dung and ditch sludge in combination with submerged tile drains may result in subsidence rates that resemble the rates before the 20th century of around 1.7 $mmyr^{-1}$ (Schothorst 1977). This was prior to the intensification of land use and the large scale drainage of peatland soils in this area that took place from the beginning of the 20th century.

Conclusions

From the data of the 3-year non-fertilized field experiment it is concluded that the contribution of subsoil (>30 cm) peat N mineralization to the total N uptake is negligible. The average total N uptake from non-fertilized fields was found to be 342 kg N ha^{-1}. Using the data from the 1-year field experiment, chemical analyses and farmers records on previous inputs, the contribution of peat mineralization to the total annual N uptake ranges between 30 and 110 kg N $ha^{-1}yr^{-1}$ for this farm. This implies that historic inputs of organic N (dung, ditch sludge, farmyard manure, slurry and unharvested herbage) determine by far most of the current N mineralization in the topsoil. Based on our findings, subsidence rates for such peatland soils with anthropogenic A horizons may be approximated at less than 2 mm per year. The fact that submerged tile drains were previously installed in these fields will probably help in preventing accelerated subsidence rates in dry years.

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