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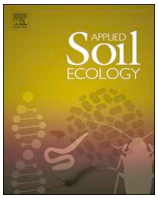

Predicting soil N supply and yield parameters in peat grasslands

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ABSTRACT

Considerable nitrogen (N) mineralization occurs in drained peat soils in use for dairy grassland, due to aerobic decomposition of soil organic matter (SOM). N losses may be limited by matching grass N uptake with N mineralization and by adapting on-farm fertilization schemes to soil N supply (SNS) and apparent N recovery (ANR). Previous attempts to predict SNS of peat grasslands from soil parameters have been unsuccessful, partly due to high variation in SNS between sites and years. In this paper, we present field data from twenty dairy grasslands on drained peat (29–65% SOM; Terric Histosols). Grass yield parameters (e.g. SNS and ANR) were compared with a comprehensive data set of soil biotic and abiotic properties measured at the start of the growing season, and with N mineralization calculated from this data. SNS ranged between 171 and 377 kg N ha^{-1} (mean: 264 kg N ha^{-1}) during the growing season. Soil N mineralization estimated by laboratory incubation and by foodweb-based production ecological calculations gave similar mean values with slightly higher coefficients of variation, but correlations with SNS were not significant. Regression analysis with soil properties showed a positive correlation between SNS and soil Ca:Mg ratio and a negative correlation between fertilized grass yield and soil C:SOM ratio. No significant models were found for ANR. Based on our data and on literature, we conclude that these parameters indicate linkages between grass yield and soil physical-hydrological properties such as soil structure and water availability. In particular, the C:SOM ratio in these soils with high organic matter content may be an indicator of water repellency, and our results suggest that grass growth was limited by drought more than by nutrient availability.

1. Introduction

Maximizing nutrient use efficiency and minimizing environmental impact are growing challenges for agriculture worldwide. In combination with increasing restrictions on the use of external inputs, this requires a re-evaluation of present farming practices (Erisman et al., 2016, 2015). Moreover, agriculture considerably influences global warming via its effect on the emission of carbon dioxide (CO$_2$) from soil carbon (C) pools into the atmosphere (Lal, 2008). This is particularly the case for agriculture on drained peat soils: these soils represent only 0.3% of the global land area but contribute 6% of the total anthropogenic CO$_2$ emission (Joosten, 2011), because of decomposition of soil organic matter (SOM) under oxic conditions (Armentano, 1980; Kasimir-Klemedtsson et al., 1997). Compared to original peat soils, agricultural peat soils contain higher amounts of nitrogen (N) due to the historical addition of organic material such as manure, crop residues and ditch sludge (Brouns, 2016; Sonneveld and Lantinga, 2011). Aerobic decomposition of SOM in drained peat leads therefore to mineralization of substantial amounts of organic N that can contribute to the N demand of crops. However, mineralized N may also be denitrified

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and lost to the atmosphere as nitrous oxide (Van Beek et al., 2004a).

To reduce N losses from dairy grasslands, grass N uptake should match N mineralization, and N fertilization rates should be advised based on reliable predictions. Under the assumption that in optimal growth conditions most mineralized N from soil is taken up by grass, the unfertilized herbage N yield can be used as a proxy for the "soil N supply" (SNS) (Hassink, 1995a; Vellinga and Andre, 1999). In the Netherlands, a site-specific prediction of SNS for mineral soils based on soil parameters such as SOM and N_{total} is used in the grassland fertilization guideline (Hassink, 1995b; Van Eekeren et al., 2010; Vellinga and Andre, 1999). On drained peat however, no site-specific SNS is currently used (www.bemestingsadvies.nl). Until c. 1980, when drainage depth in peat regions in the Netherlands was regularly increased, SNS reached up to c. 500 kg N ha^{-1} per growing season (Schothorst, 1977). SNS was positively correlated with depth of ground water table, probably due to mineralization of easily degradable N in newly drained peat layers (Van Kekem, 2004). In later studies in grasslands with stable drainage depths, SNS was generally lower (85–315 kg N ha^{-1}) and the variation was no longer explained by ground water table, but by summer rainfall (Hassink, 1995a; Sonneveld and Lantinga, 2011; Van Beek et al., 2004b; Van Kekem, 2004; Vellinga and Andre, 1999). SNS on peat is more variable and generally higher than for mineral soils (126–192 kg N ha^{-1} y^{-1}) (Hassink, 1995b; Van Eekeren et al., 2010; Vellinga and Andre, 1999). Attempts to find soil properties that can explain variation in SNS are scarce and have not been successful for peat soils (Hassink, 1996), leading to a fixed SNS of 250 kg N ha^{-1} y^{-1} in the present grassland fertilization guideline. With the high variation in realized SNS, the lack of site-specific prediction leads to low nutrient use efficiency and high losses of applied nutrients in many cases, or to insufficient fertilizer applications and unnecessarily low yields. Additionally, the fixed SNS is problematic for dairy farms on peat because it gives an over- or underestimation of the N use efficiency in the mandatory Annual Nutrient Cycle Assessment (Aarts et al., 2015). Hence, an adequate prediction of SNS on peat grasslands would benefit both farmers and society. Recently, Rashid et al. (2014) used a combination of soil incubation methods with production ecological model calculations based on abundances of soil organisms to predict N mineralization in grassland soils, and showed a good match with SNS on two peat and two sandy sites. Their results suggest that soil hydrology, chemistry and microbiology may determine SNS on peat, as well as soil meso- and macrofauna. However, this method has not yet been validated for a larger number of sites and a wider SNS range. The linkages between soil biotic and abiotic properties and yield parameters of peat grasslands remain therefore uncertain.

Under fertilized conditions, the apparent N recovery (ANR) is a measure of the uptake of applied N and may reveal potential N losses. Based on 60 years of grassland experiments in the Netherlands, Vellinga and Andre (1999) found ANR on peat of 60% at a fertilization rate of 200 kg N, which was c. 10% lower than on mineral soils. This was explained by the higher SNS of peat soils. On sandy soils, variation in ANR (35–102%) was predicted by the number of enchytraeids, possibly indicating a balanced decomposition of SOM (Van Eekeren et al., 2010). To our knowledge, ANR on peat soils has not been studied in relation to soil parameters previously.

In this paper, we address the variation in SNS, ANR and fertilized grass dry matter (DM) and N yield across twenty dairy grasslands in the western Dutch peat area. We relate these yield parameters to a comprehensive data set of soil biotic and abiotic properties, measured at the start of the growing season, and to N mineralization calculated from this data. For an adequate representation of the variation and to minimize site-specific and weather effects on the results, twenty dairy grasslands (replicates) were sampled in one growing season (Van Eekeren et al., 2010). The objective was to find soil properties that determine the variation in grass yield parameters on drained peat. We focus especially on SNS, as this value is of great importance for developing efficient site-specific fertilization schemes. In general, we hypothesize that grass yield parameters are positively correlated with parameters of soil organic matter decomposition such as potential C and N mineralization. More specifically, we hypothesize that a good estimation of SNS can be provided by production ecological calculations, or with the combination of potential N mineralization (based on laboratory incubation of sieved soil) with modeled earthworm N mineralization (which is not included in the incubation due to soil sieving).

2. Materials and methods

2.1. Experimental sites

We selected twenty dairy grasslands on drained peat soils (Terric Histosols; FAO, 2015) in the western peat area of the Netherlands. The grasslands had an average ditch water level in the summer ranging from 30 to 60 cm below soil surface and a history of mixed grazing and cutting, and were dominated by *Lolium perenne* L., *Poa trivialis* L. and *Poa pratensis* L. Other site information is provided in Table S1 (supplementary material). The year before the experiment was conducted, the grasslands received on average 140 kg N ha^{-1} as inorganic fertilizer and 216 kg N ha^{-1} as organic fertilizer (mainly slit-injected cattle slurry; not including excretion during grazing) as part of regular management by the farmers. This is in line with the Dutch fertilization guideline for grasslands on peat (www.bemestingsadvies.nl). The main soil and botanical characteristics of the twenty sites are presented in Table 1.

In each grassland, being the experimental unit, an experimental field (14 × 9 m) consisting of three plots was laid out in February 2010: two 4 × 9 m plots for grass production measurements and one 6 × 9 m plot for measurement of soil and botanical parameters (Fig. S1, supplementary material). Of the two grass production plots, one plot was fertilized with calcium ammonium nitrate (27% N) at a rate of 200 kg N ha^{-1} yr^{-1} (120 kg before the first cut and 80 kg before the second cut; this is a common rate in the peat region), whereas the other plot was not fertilized with N; both plots received ample P and K fertilizer. The 6 × 9 m plot for measurement of soil parameters and botanical composition was not fertilized at all during the year of measurements. This experimental design was used to measure three types of parameters and characterize each of the twenty grasslands in a uniform way (Van Eekeren et al., 2010): (i) the grass N yield in the plot without N fertilization, but with P and K to prevent these nutrients to become limiting, provided the SNS of these grasslands (Hassink, 1995b), (ii) the N-fertilized grass yield measured in the NPK-fertilized plot was a measure of the grass production level in the normal dairy farming practice and was used with SNS for calculation of ANR, and (iii) the soil biological, chemical and physical parameters measured at the start of the growing season and without recent fertilization provided the "baseline" soil properties of the twenty grasslands without short term effects of fertilization.

Table 1
Main soil characteristics and botanical composition of dairy grasslands on drained peat soils (n = 20) (Deru et al., 2018).

Parameter	Unit	Mean	Standard deviation	Range
Soil bulk density	g cm^{-3}	0.54	0.09	0.39–0.75
Soil organic matter (SOM)	g.100 g dry $soil^{-1}$	43.8	8.8	29.2–64.7
C_{total}	g.100 g dry $soil^{-1}$	22.4	4.5	14.2–31.8
N_{total}	g.100 g dry $soil^{-1}$	2.01	0.46	1.25–2.99
P_{total}	g.100 g dry $soil^{-1}$	0.73	0.11	0.60–0.99
pH_{KCl}	–	4.8	0.3	4.3–5.4
Average ditch water level (summer)	cm below soil surface	49	8	60–30
Monocotyledons	% cover	83	11	60–95
Dicotylendons	% cover	9	10	0–35

2.2. Grass measurements

Grass in the production plots was harvested four times in 2010 (17–21 May, 28 June-2 July, 16–20 August and 29 September-7 October) at a stubble height of 6 cm using a Haldrup plot harvester (J. Haldrup a/s, Løgstør, Denmark). Harvested grass was weighed and a sub-sample was taken for dry matter (DM) and N analysis. DM was determined after drying at 70 °C for 48 h and total N (Kjeldahl) was analyzed in dry material. The grass N yield in the grass production plot without N but with P and K fertilizer was used as a measure for the soil N supply (SNS; kg N ha^{-1}) (Hassink, 1995a; Vellinga and Andre, 1999). Apparent N recovery (ANR; kg N.kg N^{-1}), the extra N yield in relation to the amount of applied fertilizer N, was calculated as *(N yield(fertilized) – N yield(non-fertilized))/(N fertilization rate)* (Vellinga and Andre, 1999).

2.3. Soil parameters and calculations of N mineralization

Soil measurements in the 6 × 9 m plots were carried out at the start of the growing season, in April 2010, as described in Deru et al. (2018). For the present paper, we used a subset of the soil data of Deru et al. (2018) (dairy grasslands, n = 20), including 81 soil biological parameters (describing microorganisms, nematodes, enchytraeids, earthworms and microarthropods), 19 soil chemical parameters (organic matter characteristics, nutrient supply and availability) and 22 soil physical parameters (water content, texture, structure, penetration resistance). A full list of parameters is presented in Table S2 (Supplementary material), and data statistics are published in Deru et al. (2018).

For each site, we calculated the soil N mineralization during the growing season until the last grass harvest (March-September included) using the soil biological parameters of April 2010 and based on three approaches as described in Rashid et al. (2014): (i) potential N mineralization measured in laboratory incubations of soil, (ii) production ecological calculations of N mineralization by soil organisms and (iii) a combination of (i) and (ii).

(i) Potential N mineralization (μg N.g $soil^{-1}$.$week^{-1}$) was measured in laboratory incubation of field-moist samples (Deru et al., 2018). Mineralization during the growing season was estimated with the value of April for the whole period, using a Q_{10} of 3 to correct for field temperature per month. The Q_{10} of 3 was based on Bloem et al. (1994), Table 1, which shows the average *in situ* N mineralization measured in the field (average soil temperature 9.5 °C) and the potential N mineralization measured in the lab at 20 °C: the ratio is 3 in the 0–25 cm soil layer. Soil temperature (−10 cm) was taken from the nearest weather station (De Bilt) (KNMI, 2010). Upscaling to kg N ha^{-1} was done with measured site-specific soil bulk densities (Table S1).

(ii) Production ecological calculations based on the method developed by Didden et al. (1994) were carried out for protozoa, bacteria, fungi, nematodes, enchytraeids, earthworms and microarthropods. N mineralization was calculated using physiological parameter values as listed in Table S3 (Supplementary material) and with abundances and biomasses in April 2010 taken from Deru et al. (2018). The calculations are described in detail in Rashid et al. (2014). Briefly, C respiration of organisms was calculated using their individual fresh weight and abundance, then corrected for soil temperature (KNMI, 2010) with a group-specific Q_{10} value, and finally converted to N mineralization with assimilation efficiency (A_e), production efficiency (P_e) and body and food C/N ratio (Table S3). For protozoa (amoebae and flagellates), abundance in peat soils was taken from Finlay et al. (2000) as a fixed amount for all sites. For bacteria and fungi, C respiration was calculated with their biomass (kg C ha^{-1}, using site-specific soil bulk density) and respiration rate constants (0.27 and 0.29, respectively). Body weights of enchytraeids, endogeic and epigeic earthworms were corrected for gut content (7%, 15% and 10% of the fresh weight, respectively (Persson et al., 1980; Van Vliet et al., 2007)). In contrast to Rashid et al. (2014), production ecological calculations in this paper include site-specific data on nematodes and microarthropods, and calculations were based on organism abundance in April only. N mineralization was calculated over the period in which grass production and SNS were measured (March to September: 7 months) with soil temperatures taken from the weather station De Bilt (KNMI, 2010) for all sites.

(iii) Potential N mineralization from approach (i) was combined with modeled earthworm N mineralization from approach (ii) (which is not included in approach (i) due to soil sieving) following Rashid et al. (2014).

2.4. Statistical analyses

Statistical analysis was performed using Matlab (version 8.6 R2015b, The Mathworks). Before further statistical analyses, the Lilliefors test (performing a Kolmogorov-Smirnov test for normality with mean and variance unknown) was carried out on non-transformed parameter values (x) and on log-transformed values with added constants (1 or 10). When necessary to obtain a normal distribution, log-transformed parameter values were used in the further statistical analyses. Pearson's correlation coefficients were calculated for all parameters. Furthermore, linkages between grass yield parameters and soil properties were explored based on the method used by Van Eekeren et al. (2010) and Andersson et al. (2011), using stepwise linear regression with permutation tests to determine model significance. For each grass yield parameter (SNS, ANR, fertilized N yield and fertilized DM yield), potential regression models were generated based on separate sets of descriptive parameters (soil biological (set B), soil chemical (set C), soil physical (set P), or all parameters combined (set BCP)), from which a minimum of one and a maximum of three parameters were selected. Subsequent selection of statistically significant models was based on random permutation tests performed on the complete stepwise regression procedure. For each maximum number (1–3) of descriptive parameters, we tested for 999 permutations whether the permuted r^2 was equal to or above 90% of the calculated true r^2. In other words, we assessed if there was a significant gap (> 10%) between the calculated true r^2 and the distribution of all permuted r^2s. Random permutation tests resulting in a *P*-value below 0.05 were considered to be significant.

3. Results

3.1. Grass yield parameters

Grass yield parameters are presented in Table 2. Mean SNS was 264 kg N ha^{-1}, and fertilized N yield was 130 kg N ha^{-1} higher. This resulted in a ANR of 0.65 kg N kg N^{-1}. SNS showed a much higher variation across sites than fertilized yield. SNS was positively correlated with fertilized N yield ($r = +0.83$, $P < 0.01$) and negatively with ANR ($r = -0.69$, $P < 0.01$).

Table 2

Grass yield parameters in dairy grasslands on drained peat soils during the growing season (total of four cuts): means, coefficients of variation and ranges (n = 20).

Parameter	Unit	Mean	CV (%)	Range
Soil N supply (SNS)	kg N ha^{-1}	264	18.9	171–377
Apparent N recovery (ANR)	kg N.kg N^{-1}	0.65	21.8	0.41–1.00
Fertilized N yield	kg N ha^{-1}	394	9.2	335–480
Fertilized DM yield	Mg DM ha^{-1}	13.1	9.4	11.6–15.9

Table 3

Calculated N mineralization (kg N ha^{-1} during March – September included) in dairy grasslands on drained peat soils: means, coefficients of variation and ranges (n = 20).

Parameter	Mean	CV (%)	Range
Potential N mineralization (PNM)	238.1	37.2	93–406
Production ecology	263.3	23.8	168–420
Protozoa	41.5	0	–
Bacteria	47.7	28.9	25–79
Fungi	52.1	30.9	27–80
Nematodes	7.9	19.6	5–13
Enchytraeids	14.3	35.3	5–23
Earthworms	98.7	53.0	25–219
Microarthropods	1.0	38.7	0–2
PNM + Earthworms	336.8	28.4	207–581

3.2. Soil N mineralization

The mean value and range of potential N mineralization determined by laboratory incubation and subsequently scaled up to mineralization at field temperature during the growing season were somewhat lower, but comparable to the mean and range of production ecological calculations (Table 3). The groups of soil organisms contributed not equally to the total N mineralization: N mineralization by earthworms was highest (37%), that of protozoa, bacteria and fungi together was 53%, and that of enchytraeids, nematodes and microarthropods together was 10%. There was no significant correlation between potential N mineralization by laboratory incubation and N mineralization by soil organisms ($r = -0.19$, $P > 0.05$). Excluding earthworm mineralization from the total production ecological mineralization did not improve the correlation with potential N mineralization (which is measured in sieved soil without earthworms) ($r = -0.12$, $P > 0.05$).

3.3. Grass yield linked with N mineralization and soil properties

Mean SNS was 79% of mean potential N mineralization by laboratory incubation plus earthworm N mineralization and N deposition, and 99% of total N mineralization by soil organisms (production ecological calculations) plus N deposition (15 kg N ha^{-1}; as used by Rashid et al. (2014)) (Fig. 1). However, no significant correlations ($P > 0.05$) were found between SNS and potential N mineralization by laboratory incubation ($r = +0.18$), SNS and potential N mineralization by laboratory incubation plus earthworm N mineralization ($r = +0.22$) or SNS and total N mineralization by soil organisms through production ecological calculations ($r = +0.24$). Significant correlations were found between yield parameters and various soil biological, chemical and physical parameters (Table 4). Stepwise regression with *P*-values based on permutation tests resulted in models with higher *P*-values, and these models were significant with chemical and physical soil parameters only (Table 5). SNS was positively correlated with Ca:Mg ratio (Fig. 2a), also in combination with C:SOM ratio or soil air content at pF 2 (negative regression weights) (Table 5). For ANR, no significant regression model was found. Fertilized N yield was described by a combined model with Ca saturation (positive regression weight) and C:SOM ratio (negative regression weight). Similarly, fertilized DM yield was described by C:SOM ratio (negative correlation, Fig. 2b) with increased model performance when Ca saturation (positive regression weight) was added. However, the model for fertilized DM yield with highest r^2 was achieved with soil physical parameters: penetration resistance at 0–10 cm, load bearing capacity (both negative regression weights) and sand percentage (positive regression weight) (Table 5).

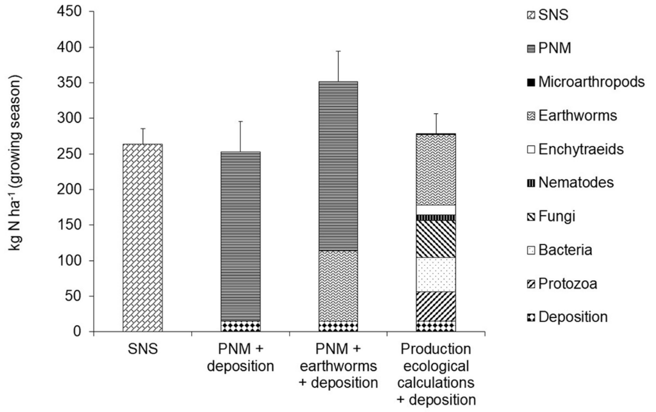

Fig. 1. Comparison of soil N supply (SNS) and three methods to predict it, based on measurements in 20 dairy grasslands on peat soils. SNS: grass N yield in unfertilized plots; PNM: potential N mineralization determined by laboratory incubation of sieved soil; earthworms: N mineralization by earthworms estimated by production ecological calculations. Error bars represent 2 × SE (n = 20) on the total.

4. Discussion

The variation in SNS measured across our twenty dairy grasslands on drained peat (171–377 kg N ha^{-1} yr^{-1}) falls within the range found on peat soils by other authors (Hassink, 1995a; Sonneveld and Lantinga, 2011; Van Beek et al., 2004b; Van Kekem, 2004; Vellinga and Andre, 1999), and is large. This underlines the need of a prediction tool for SNS that is sensitive to differences across grassland sites within the peat region to arrive at optimal use of N fertilizer. The aim of this study was to find soil parameters that predict the observed variation in SNS and other grass yield parameters across twenty dairy grasslands on peat.

4.1. Grass N uptake and soil N mineralization

In contrast with our hypothesis, the grass production parameters were not significantly explained by C or N mineralization parameters. For SNS, this is in accordance with the work of Hassink (1996), who found no correlation between SNS and soil organic N content, microbial N and N mineralization in similar soils. However, Rashid et al. (2014) suggested production-ecological modeling to explain the gap between SNS and soil N mineralization calculated from laboratory incubation measurements, based on two peat grasslands. In our data from twenty grasslands, average SNS was close to total N mineralization by soil organisms or potential N mineralization (difference < 15 kg N ha^{-1}), but lower than potential N mineralization plus earthworm N mineralization (difference: 88 kg N ha^{-1}; Tables 2 and 3 after correction for N deposition). Assuming relatively low N losses from unfertilized peat grasslands (denitrification: 20–40 kg N ha^{-1} y^{-1} (Van Beek et al., 2004b); leaching to ground water: < 10 kg N ha^{-1} y^{-1} (Van Beek, 2007)), the average SNS of the twenty grasslands appears to be well in line with estimated N mineralization from soil organisms. However, to increase the N use efficiency of individual dairy grasslands within a region, not only an accurate match between means is needed, but also the variation across sites must be well predicted. The abovementioned differences of means between SNS and estimated soil N mineralization have high standard deviations (70–97 kg N ha^{-1}), and the correlation between these parameters were low and not significant. So, our calculations of N mineralization did not appear to yield suitable predictors for SNS for individual grasslands.

A possible explanation for the absence of significant correlations between SNS and soil N mineralization may be the lack of site-specific data on factors that influence N availability, such as protozoa, N deposition, N denitrification, soil temperature, as well as temporal dynamics in soil moisture and abundance and activity of soil organisms during the growing season. Of those factors, protozoa contribute substantially to the N mineralization in agricultural soils (De Ruiter et al., 1993) and are sensitive to soil moisture (Van Dijk et al., 2009). The

Table 4
Significant Pearson's correlations between grass yield parameters and soil biological (set B), soil chemical (set C) and soil physical (set P) parameters from Deru et al. (2018) (dairy grasslands, n = 20).

Set	Parameter	Soil N supply (SNS)	Apparent N recovery (ANR)	Fertilized N yield	Fertilized DM yield
B	Fungal biomass				0.47*
	Nematode taxa		−0.46*		
	Nematode plant parasitic index	−0.49*	0.49*		
	Enchytraeids (number/biomass)				0.48*/0.45*
	Enchytraeus enchytraeids (number)			0.51*	
	Earthworm taxa		0.52*		
	Collembola taxa				0.46*
	Acari taxa		0.47*		
	Bacterivorous microarthropods (number/%)			0.45*/0.48*	
	Fungivorous microarthropods (%)			0.61**	0.64**
	Omnivorous microarthropods (%)		−0.49*		
	Combined abundance index				0.50*
C	Plant available P (P_{AL})			0.45*	
	pH_{KCl}			0.46*	
	C:SOM ratio	−0.56*		−0.55*	−0.72**
	% Calcium saturation	0.52*		0.64**	0.49*
	% Magnesium saturation		0.46*		
	Ca:Mg ratio	0.70**	−0.47*	0.59**	0.52*
P	Water content at pF 2		−0.45*		
	Air content at pF 2	−0.62**	0.62**		−0.45*
	% Clay	−0.52*			−0.51*
	% Sand	0.55*		0.59**	0.65**
	Penetration resistance 0–10 cm			−0.45*	−0.70**
	Penetration resistance 10–20 cm				−0.64**
	Load bearing capacity			−0.49*	−0.58**

* Significance level $0.01 < P < 0.05$.
** Significance level $P < 0.01$.

Table 5
Permuted stepwise regression analysis with grass yield parameters against soil biological (set B), chemical (set C) and physical (set P) parameters from Deru et al. (2018) (dairy grasslands, n = 20), including a minimum of one and a maximum of three descriptive parameters in the model. Models based on more than one set are computed with the combined data from those sets. Results are presented for significant models only ($P < 0.05$; P calculated with permutation tests).

Grass yield: response parameter	Set	1st model parameter	2nd model parameter	3rd model parameter	P	r^2
Soil N supply (SNS)	C	+ Ca:Mg ratio			0.021	0.49
	C	+ Ca:Mg ratio	− C:SOM ratio		0.049	0.56
	CP	+ Ca:Mg ratio	− Air content pF 2		0.045	0.66
Apparent N recovery (ANR)	–				n.s.	
Fertilized N yield	C	+ % Ca saturation	− C:SOM ratio		0.031	0.57
Fertilized DM yield	C	− C:SOM ratio			0.013	0.53
	C	− C:SOM ratio	+ % Ca saturation		0.017	0.63
	P†	− Pen. res. 0–10 cm			0.009	0.49
	P†	− Pen. res. 0–10 cm	+ % Sand		0.004	0.74
	P†	− Pen. res. 0–10 cm	+ % Sand	− Load bearing capacity	0.009	0.78

† Same models found for the combined set BCP; Pen. res.: penetration resistance.

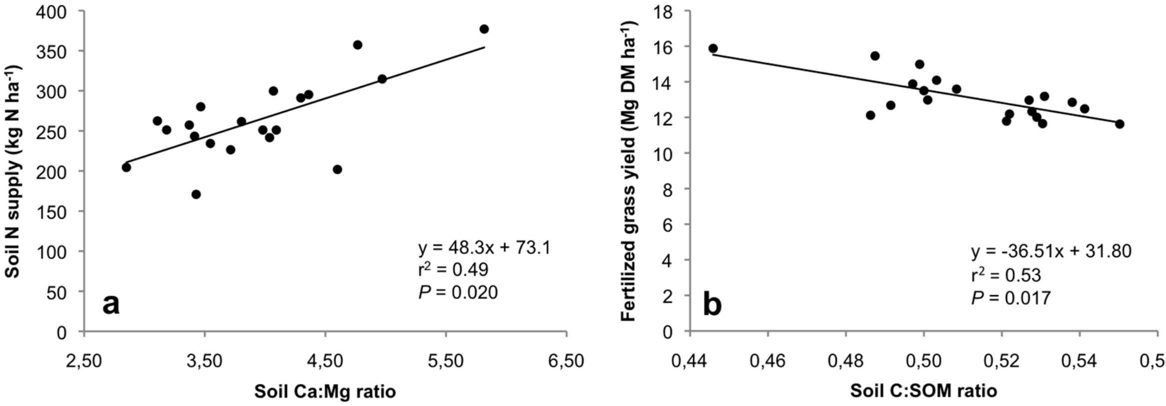

Fig. 2. Regression models for soil N supply (SNS) as a function of soil Ca:Mg ratio (a), and for fertilized grass dry matter (DM) yield as a function of soil C:SOM ratio (b) in 20 dairy grasslands on peat soils. P-values calculated with random permutation tests.

moisture content in the rooted zone of drained peat is high in winter and low during dry periods (Schothorst, 1982). Although the twenty grasslands in this study were situated within the same region and climatic conditions and had comparable management of ditch water level, individual differences in soil hydrology may have influenced N mineralization and grass N uptake considerably. In relation to that, N mineralization or N availability may not have been the most limiting factor for grass N uptake, at least during part of the growing season. Schothorst (1982) showed strong stagnation of grass growth in dry summers on peat soils with relatively high groundwater levels, due to nearly absent capillary flow. Moreover, deep grass root development in peat is hindered, which may be caused by the high groundwater level during the winter in combination with subsoil acidity (Lynch and Wojciechowski, 2015; Schothorst, 1982).

Summarizing, we must reject the hypothesis that simple estimations of the N mineralization during the growing season, based on soil data at the start of the growing season, can be used as predictors for SNS of dairy grasslands on peat soils. Possibly, the production ecological approach to calculate N mineralization needs more site-specific and temporal data on abundance and activity of soil biota and on soil temperature and water availability. However, for the development of a site-specific fertilizer N application recommendation, SNS must be predicted by simple parameters that can be measured before or at the start of the growing season. Therefore, it may be relevant to explore factors other than N availability during the season that influence SNS and herbage yield parameters, for example water availability or soil structure. This is discussed in the next section.

4.2. *Prediction of SNS and fertilized grass yield with soil properties*

Although variation in SNS did not correlate with that of calculated N mineralization, it did so significantly with various soil chemical and physical properties (Table 4), indicating that N yield was not (only) limited by N availability. SNS was explained by Ca:Mg ratio and soil air content at pF 2 (Table 5). In a linear model with Ca:Mg ratio as single explanatory variable, SNS increased with $48\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ for each unit increase in Ca:Mg (Fig. 2a), reaching the highest value at a Ca:Mg ratio of about 6. This is close to the “ideal” Ca:Mg ratio of 65:10 which has been suggested in the past for arable crops on mineral soils (Albrecht, 1975; Bear and Toth, 1948). This result is surprising, because the existence of an “ideal” Ca:Mg ratio has been challenged based on empirical studies showing no influence of cation ratios on soil fertility (Kopittke and Menzies, 2007). However, Dontsova and Norton (2002) showed that an increase in Mg saturation (with decreased Ca:Mg ratio) on clay soils reduced aggregate stability and water infiltration into the soil. In our study, neither Ca saturation, Mg saturation, nor Ca:Mg ratio was significantly correlated with water infiltration rate, but Ca saturation was positively correlated with soil crumbliness ($r = +0.50$; $P < 0.05$) and Mg saturation was negatively correlated with water holding capacity (water content at pF 2; $r = -0.58$; $P < 0.01$). These correlations may indicate differences in soil physical-hydrological properties across sites related to Ca and Mg saturation in line with Dontsova and Norton (2002). Apparently, a combination of higher Ca saturation (more crumbly soil structure) and lower Mg saturation (higher water holding capacity) led to higher SNS in our study. Both SNS and Ca:Mg ratio did not correlate significantly with soil $\mathrm{pH_{KCl}}$, thus a causality between Ca:Mg ratio and SNS is presumed not to be driven by differences in soil acidity and its effects on N mineralization. Therefore, a causality between SNS and Ca:Mg ratio seems to be related to soil structure and water availability.

SNS correlated less strongly with Ca saturation than with the Ca:Mg ratio, but for fertilized N yield the opposite was found (Table 4). Ca saturation itself – but not Ca:Mg ratio – was significantly correlated to $\mathrm{pH_{KCl}}$ ($r = +0.84$; $P < 0.01$). Accordingly, fertilized N yield – but not SNS – correlated positively with $\mathrm{pH_{KCl}}$ ($r = +0.46$; $P < 0.05$). The amount of dissolved organic carbon and rate of microbial breakdown are known to increase with soil pH (Marschner and Wilczynski, 1991; Oste et al., 2002; You et al., 1999), resulting in nutrient mineralization that can benefit plant growth. However, if the relationship between grass N yield and Ca saturation was influenced by soil pH and higher N mineralization, we would have expected a stronger correlation in the unfertilized plots (SNS) instead of in the fertilized plots (fertilized N yield). This may be an indication that on these drained peat soils, grass N yield was not limited by N availability, but by other (soil) factors.

Both fertilized DM and N yields were negatively correlated with C:SOM ratio (Table 4), but not with C_{total} or SOM individually (data not shown). C:SOM ratio was also selected as second model parameter after Ca:Mg in explaining the variation in SNS. The C:SOM ratio measured in our grasslands ranged between 0.45 and 0.55, which represents the lower end of the range (0.4–0.7) that can be expected in soil (Pribyl, 2010). In soils with organic C contents higher than 10%, C:SOM ratio was found to be 0.54 in the topsoil and 0.61 in the subsoil, indicating a distinction with depth (Pribyl, 2010). Accordingly, Klingenfuß et al. (2014) observed lower C:SOM ratios in drained topsoils than in water saturated subsoils of peatlands, due to lower C contents in the topsoils. A reduction of the topsoil C:SOM ratio in drained peat may occur due to secondary soil development characterized by mineralization and humification (Kalisz et al., 2010; Klingenfuß et al., 2014), in addition to input of new organic matter from manure and grass residues in dairy grasslands. In our study, the relation between C:SOM ratio and grass yield did not seem to be linked to nutrient mineralization because the correlation was stronger in fertilized plots than in unfertilized plots, and stronger for DM yield than for N yield. As far as we know, C:SOM ratio has not previously been selected as explanatory parameter for grass yield. In our data set, C:SOM ratio was positively correlated with penetration resistance ($r = +0.69$; $P < 0.01$), which is sensitive to both soil structure (compaction, bulk density) and soil moisture (Elbanna and Witney, 1987). Therefore, the C:SOM ratio of soils high in organic matter (> 25%) may be an indicator of soil physical and hydrological properties that influence grass yield, in line with the relation between Ca:Mg ratio and SNS.

A possible explanation for the correlation between C:SOM ratio and grass yield may be that in our case, C:SOM ratio is an indicator of soil water repellency, which affects soil water availability for both plant growth and soil biota regulating N mineralization. Water repellency of soil is mainly caused by organic molecules consisting of a non-polar hydrophobic CH chain with a polar hydrophilic functional group at one end (Doerr et al., 2000) and there is a positive relation between molecular weight and water repellency (Mao et al., 2014; Morley et al., 2005). Large organic molecules have generally longer C-chains and are relatively more carbon-rich, and thus have a higher C:SOM ratio. Soil C:SOM ratio may therefore be an indicator of water repellency in peat and this could explain the correlation with grass yield in the present study. Despite the generally high water levels in ditches and surface water in peat areas (30 to 60 cm below soil surface), it is known that grass growth on peat soils can easily be limited by drought during summer (Schothorst, 1977; Van der Meer et al., 2004), because water transport from ditches and groundwater to the rooted soil layer is strongly hampered (Schothorst, 1982). In these soils, water-holding capacity of the rooted zone may therefore be an important factor for grass growth. As a result of differences in water repellency of organic soils (Berglund and Persson, 1996; Dekker and Ritsema, 2000), water availability may differ among sites, especially following rewetting after a drought period (Schwärzel et al., 2002). Therefore, in temperate climates, water repellency effects occur mainly after the summer, i.e. at the time of increased precipitation while temperature and radiation are still sufficient for grass growth. This is exactly what was found in the present study: C:SOM ratio correlated most strongly with the fertilized DM yield of the 4th cut (Table 6); the regrowth period of this cut was wet and followed a long dry period in June and July (KNMI, 2010). So, C:SOM ratio appeared to indicate water repellency of the soil, which seemed to have influenced grass yield negatively.

Table 6
Pearson's correlations between C:SOM ratio and fertilized grass yield parameters per grass cut.

	1st cut	2nd cut	3rd cut	4th cut	Total
Fertilized N yield	−0.34	+0.18	−0.35	−0.69	−0.55
Fertilized DM yield	−0.53	−0.15	−0.31	−0.73	−0.72

Summarizing, we observed correlations between grass yield and soil properties (Ca:Mg ratio, Ca saturation, C:SOM ratio) suggesting that variation in yield across sites was more influenced by soil physical-hydrological factors such as water availability, than by N mineralization.

4.3. Challenges for minimizing losses and maximizing grass yield on drained peat soils

Our results indicate that high N losses can potentially occur in fertilized grass, because mean ANR was 0.65 kg N per kg fertilizer N applied, with a minimum value of 0.41 kg N (Table 2). Hence, on average, 35% of the applied N was not harvested in herbage but may have been denitrified (Kroeze et al., 2003) or leached to the groundwater if not stored in soil. Although a mean ANR of 0.6–0.7 is common in grassland (Van Eekeren et al., 2010; Vellinga and Andre, 1999), an increased N utilization would benefit farmers and society. Especially on peat soils, that have a SNS of 171–377 kg ha^{-1} and for which N fertilizer rates are based on a theoretical SNS of 250 kg ha^{-1}, adapting the N fertilization to the local SNS may increase ANR and minimize N losses. In our study, predictors for SNS, such as Ca:Mg ratio and C:SOM ratio, indicate that SNS is sensitive to differences in soil physical-hydrological properties. Although these predictors explained part of the spatial variation in SNS during one growing season, additional research is needed to quantify their sensitivity to variation across years due to weather and climate differences.

5. Conclusions

Our study on twenty dairy grasslands on drained peat soils showed that SNS was high in comparison to mineral soils. The ANR was 65% on average, which is in line with values on mineral soils and indicates that considerable losses of applied N may occur in fertilized peat grasslands.

Mean SNS corresponded to mean N mineralization by soil organisms calculated from measurements at the start of the growing season. However, the site-specific variation in SNS and other grass yield parameters was not significantly correlated with soil N mineralization calculated on the basis of soil data measured at the start of the growing season, but was significantly correlated with Ca:Mg ratio, Ca saturation and C:SOM ratio. Based on these and other correlations in our data set and on literature, we infer that grass yield was more influenced by water availability than by N mineralization, and that especially the correlation with C:SOM ratio was indicative of soil water repellency that influenced grass yield negatively. Further research is required to address the causality of relationships between grass yield, water availability and soil properties of drained peat and to develop prediction tools, taking into account the variation across sites and years.

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Appendix A. Supplementary data

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