



Soil nitrogen supply of peat grasslands estimated by degree days and soil organic matter content

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Abstract Accurate estimates of the quantity and rate of soil nitrogen supply (SNS) are essential to increase soil and farm N use efficiencies, in particular for soils high in organic matter. The objective of this work was to enhance the empirical understanding of the SNS of dairy grasslands on peat soils, using soil properties and weather variables. Data were collected from studies on herbage N uptake carried out between 1992 and 2017 in the western peat district of the Netherlands. For the period between March to mid October, SNS was estimated from the sum of mean growing season daily temperatures, soil organic matter (SOM) and applied calcium ammonium nitrate (CAN) N with a residual standard error of 25–27 kg ha⁻¹. Each °C growing season temperature sum affected SNS by 78–90 g ha⁻¹ and each g SOM per 100 g dry soil

affected SNS by 3.6–3.9 kg ha⁻¹, respectively. SNS was equally estimated for conditions with and without CAN fertilisation. Validation with data from independent field trials showed similar impacts of SOM and growing season temperature sum on SNS. The error of prediction of the presented models, however, was still too large for direct on-farm application and led to underestimations for a specific site. Nevertheless, the obtained models allow for an increased understanding of soil and farm N balances. The models can therefore be used for improved temporal and spatial SNS-adapted farming practice advice, which can potentially lead to reduced soil and farm N surpluses.

Keywords Histosols · Nitrogen efficiency · Mineralisation · Fertilisation · pH · Weather

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Introduction

In temperate climates, drained peatlands are often in use as grassland for dairy farming (Joosten et al. 2017; Van Kekem 2004). Drained peatlands are associated with significant C and N losses, greenhouse gas production and soil subsidence (Urák et al. 2017). Dairy farming on peat soils often results in farm N use efficiencies—defined as the amount of N output relative to the N input of the farm—that are relatively lower than that on mineral soils because of the high levels of soil N mineralisation (De Visser et al. 2001;

Van Beek et al. 2009). Herbage N uptake and content are generally higher in dairy grasslands on peat soils than on mineral soils, largely due to higher levels of N mineralisation (De Visser et al. 2001; Deru et al. 2019; Van Beek et al. 2009; Van Kekem 2004). The relatively high herbage N content of dairy grassland systems on peat soils often leads to rations exceeding cows' N requirements, which consequently result in greater animal and farm N surpluses and losses to the environment, compared to dairy grassland systems on mineral soils (De Visser et al. 2001).

Accurate estimates of the temporal and spatial variation of herbage N uptake from soil mineralisation, i.e. the soil N supply (SNS), are essential to improve the N use efficiencies of farming systems (Rütting et al. 2018). Accurate SNS estimates can contribute to improved soil and farm N balance estimates (Schröder et al. 2019) and improved SNS-adapted fertilisation, grazing and harvesting strategies (De Visser et al. 2001; Hassink 1995; Loaiza et al. 2016; Lobos Ortega et al. 2016; Ros et al. 2011; Rütting et al. 2018; Velthof et al. 2009). The SNS of dairy grassland has been reported to vary between 171 and 377 kg ha⁻¹ in the western peat district of the Netherlands (Deru et al. 2019; Sonneveld and Lantinga 2011). However, the estimation accuracy of SNS for dairy grasslands on peat soils has remained relatively low (Deru et al. 2019; Ros and Van Eekeren 2016; Vellinga and André 1999). As a consequence, in the current mandatory Dutch Annual Nutrient Cycling Assessments (ANCA) and current fertilisation advice, annual SNS of dairy grasslands on peat soils is estimated at 235 and 250 kg ha⁻¹, respectively (Bemestingsadvies 2014; Schröder et al. 2019). Dutch farm management advice for peat soils is therefore currently not adapted to spatial and temporal variations of SNS (Bemestingsadvies 2014).

Several studies showed a positive relationship between soil organic matter (SOM) content and the SNS for mineral soils (Hassink 1995; Van Eekeren et al. 2010) and peat soils (Vellinga and André 1999). Temperature, fluctuations in groundwater level and moisture content of the soil affect the biological processes involved in mineralisation (Boxem et al. 1975; Macduff and White 1985; Verloop et al. 2014). Ros et al. (2015) showed that progress can be made in the SNS estimation of grassland on mineral soils by integrating soil properties and weather data, and several models have been developed describing soil

N mineralisation of grass- and cropland using soil properties and weather data (e.g. Van der Burgt et al. 2006). However, there is no known research integrating soil properties and weather variables for the estimation of annual SNS of dairy grasslands on peat soils.

Many herbage N uptake measurements have been carried out on dairy grasslands on peat soils, over the last decades. This allows for multiple data set analyses of SNS. These measurements were partly carried out in conditions without N application, which allowed for direct deduction of SNS (Hassink 1995; Jarvis et al. 1996; Warren and Whitehead 1988; Deru et al. 2019; Van Kekem 2004; Vellinga and André 1999), and partly in conditions with calcium ammonium nitrate (CAN)-N application. However, if the effects of CAN-N application and SNS on herbage N uptake can be unravelled, data from conditions with and without CAN-N application can both be used for site-specific SNS estimations.

Therefore, the objective of the current work is to enhance the empirical understanding of SNS of dairy grasslands on peat soils in relation to soil properties, weather variables and CAN-N applications, in order to improve the accuracy of SNS estimations. Two hypotheses were used: (1) SNS can be more accurately estimated when considering soil properties and weather variables, compared to using only soil properties; and (2) SNS is not affected by CAN-N fertilisation within a growing season, i.e. soil N mineralisation contributes equally to SNS, regardless of the presence and rate of CAN-N fertilisation.

Material and methods

Data collection and selection

Data were collected from studies on herbage N uptake at drained terric histosols (IUSS Working Group WRB 2015) in the western peat district of the Netherlands carried out between 1990 and 2017. The following data selection criteria were applied:

- (1) Data had to have been collected from sites which were in use as production grasslands within a dairy farming system for multiple years before the year of measurements;

- (2) Herbage dry matter yields and total N content had to have been determined per harvest in the first year after cessation of the use of organic inputs;
- (3) Yields from at least two harvests had to have been determined using a 'Haldrup' small plot harvester (J. Haldrup a/s Løgstør, Denmark), mowed at a stubble height of 4–6 cm on an open plot (e.g. without potential disturbance of the plots such as top fencing);
- (4) If inorganic N was applied in the year of measurements, it had to have consisted only of calcium ammonium nitrate (CAN, 27% N);
- (5) Data had to have been collected from studies in which at least one treatment did not receive any CAN applications;
- (6) Data had to have been collected from sites at which the SOM content (NEN 5754) was ≥ 25 g 100 g dry soil⁻¹ and soil pH (pH-KCl, NEN ISO 10,390) was analysed, both at 0–10 cm below surface;
- (7) Data had to have been collected from sites in which ditchwater levels were maintained at maximal 60 cm below field surface, and in which the average lowest groundwater level was 50–80 cm below field surface (De Vries et al. 2003). These criteria were used since ditch- and groundwater levels have been shown to affect herbage N uptake of grasslands on peat soil (Boxem et al. 1975; Schothorst 1977).

In total, data were collected of 209 treatments from 11 studies that fulfilled the selection criteria (Table 1). Studies were carried out at 12 experimental sites, and at the sites between 1 and 11 different fields were used (Fig. 1).

Soil temperature and moisture content were not recorded in most studies. Daily mean temperatures, precipitation sums and long-term weather means, for the 1970–2017 period, were retrieved from the nearest weather station (de Bilt, KNMI, the Netherlands) (Fig. 1). Validated interpolated meteorological data were not available for each experimental site, over this period (KNMI, the Netherlands).

Conditions at experimental sites

Experimental sites had a humified topsoil horizon and either a mesotrophic subsoil (sites A, B, K and L) or eutrophic subsoil (sites C–J).

Mean N deposition in the study area was estimated to have decreased from 37.5 to 23.2 kg ha⁻¹ between 1992 and 2017 (Wichink Kruit and Van Pul 2018). Influence of local sources on N deposition was considered negligible, since the distance of the experimental sites to the nearest farms was at least 150 m (Sommer et al. 2009).

Study sites were permanent grasslands with an almost continuous N input before the year of measurements. Therefore, it was assumed that at the sites soil organic N had reached a near-equilibrium state between the gain via organic and inorganic inputs, biomass turnover and microbially induced losses (Hassink 1995; Sonneveld and Lantinga 2011). SNS was determined as the herbage N uptake in the first year after cessation of organic and inorganic N inputs (Deru et al. 2019; Hassink 1995; Jarvis et al. 1996; Sonneveld & Lantinga 2011; Van Eekeren et al. 2010; Van Kekem 2004; Vellinga and André 1999; Warren and Whitehead 1988). In addition, data from conditions in which CAN-N was applied were selected to test the hypothesis whether CAN-N applications do affect SNS within a growing season. Data selection was limited to studies in which CAN was used as inorganic N fertiliser, as other inorganic fertiliser types than CAN were only used in a few studies and fertiliser type has been shown to affect herbage N uptake (e.g. Antille et al. 2015).

Before the year of measurements, organic and inorganic inputs at the experimental sites followed agricultural practices and regulations and, therefore, were rather constant. Mean N application ranged from 246 to 270 kg ha⁻¹ for mineral fertiliser and from 293 to 308 kg ha⁻¹ for animal manure, in the 1992–1997 period. As a result of legislations mean N application decreased to between 92 and 116 kg ha⁻¹ for mineral fertiliser and between 218 and 240 kg ha⁻¹ for animal manure, from 2007 onwards (LMN 2019). During measurement years, phosphorus and potassium applications (applied as inorganic fertilisers) met recommended standards ensuring that these nutrients were not limiting herbage growth.

The mean estimated starting day for spring herbage growth was 5 March \pm 17 days, of the studies from

Table 1 Details of studies from which data were selected

Study	Data source	Years of measurements	Experimental site (s)	Fields (n)	Collected treatment means (n)	Treatment means from conditions without N application (n)	Max. no. of harvests year ⁻¹	CAN-N fertilisation ranges, kg ha ⁻¹ year ⁻¹	Soil organic matter, g 100 g dry soil ⁻¹ (0–10 cm)	pH-KCl
A	Wageningen Livestock Research, unpublished	2002, 2003	G	2	33	11	5	0–260	49	4.8–4.9
B	Wageningen Livestock Research, unpublished	2002, 2003	G	2	33	11	5	0–260	41	4.9; 5.0
C	Hoving et al. (2008)	2004	G	4	8	4	5	0–226	46–56	4.7
D	Holshof and Van Houwelingen (2012)	2005	G	1	4	1	5	0–240	57–58	4.6–4.7
E	Deru et al. (2018)	2010	A, B, D, F-L	18	36	18	4	0–240	29–65	4.3–5.2
F	Deru et al. (2019)	2015	C, G, I	3	3	3	4	0	34–44	4.5–4.9
G	Louis Bolk Institute, unpublished	2015	G	1	2	1	4	0–120	56	4.5
J	Hofstede et al. (1995); Hofstede (1995a, b)	1992–1994	G	3	41	14	7	0–607	33–64	4.5–5.5
K	Wageningen Livestock Research, unpublished	1995	G	7	7	7	6	0	32–56	4.6–5.2
L	Bussink et al. (2014)	2011, 2012	G	2	32	16	5	0–360	54–56	4.6–4.8
H	Louis Bolk Institute, unpublished	2017	E	9	9	9	5	0–250	27–52	4.5–6.6

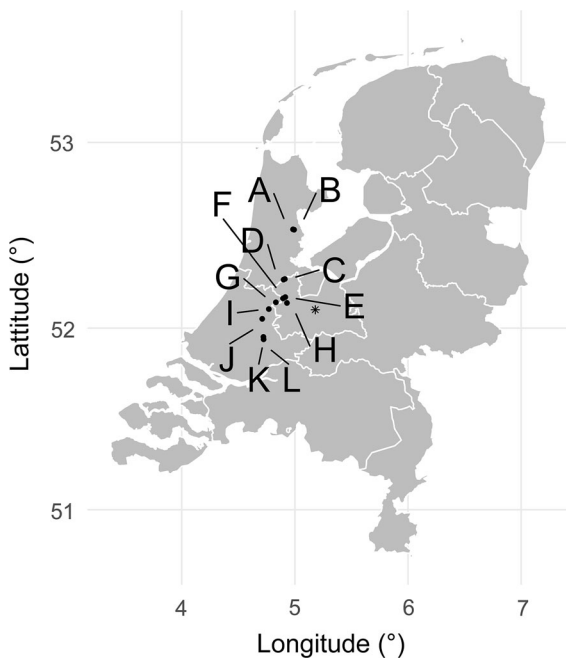


Fig. 1 Experimental sites of studies from which data were selected (closed dots) and location of weather station de Bilt (asterisk). Experimental sites were at Zeevang (a, 2 fields; b, 2 fields), Ronde Hoep (c, 2 fields; d, 1 field), Wilnis (e, 9 fields; f, 2 fields; h, 2 fields), Zegveld (g, 11 fields), Bodegraven (i, 2 fields), Reeuwijk (j, 1 field) and Krimpenerwaard (k, 2 fields; l, 2 fields)

which data were selected. The mean growing period in which data were registered lasted 213 ± 15 days and during this period mean herbage dry matter yields were $11,619 \pm 1872$ kg ha⁻¹.

Calculations and statistical analyses of the collected data

Herbage N uptake data from different mowing dates, fertilisation rates, experimental sites, fields or years, in each of the studies, were considered as separate treatments. Cumulative winter temperatures, a herbage N uptake starting day for the first harvest, growing season temperature sums, precipitation deficits, CAN-N application rates and herbage N yields were added to each record. Cumulative winter temperatures were calculated as the sum of mean daily temperatures (°C) between 1 December and 28 February of the winter preceding the growing season. The starting day of herbage N uptake in spring was assumed to be at a temperature sum of 240 °C,

calculated as the sum of positive mean daily temperatures since 1 January (De Gooijer and Jagtenberg 1968). The growing season temperature sum was calculated as the sum of positive mean daily temperatures (°C), cumulated from the assumed starting day of herbage N uptake onwards. Precipitation deficits were calculated as the cumulative difference between mean precipitations (1970–2017) and actual daily precipitation.

Data were split into an independent calibration and a test data set, and a subset was made of both data sets including only conditions without N application. Data from studies carried out at other experimental sites than G (Zegveld) and in which no CAN-N fertiliser was applied were evenly distributed over the calibration and test data set. Descriptive statistics of the different data sets are presented in Table 2.

Data were tested for normality and homogeneity of variance. Subsequent statistical analyses were carried out in three steps;

- (1) Analyses were conducted with the objective to assess the effect of soil properties and weather variables on annual SNS per degree of growing season mean daily temperature sum, using a subset of the calibration data set with treatment means from conditions without CAN-N application. First, linear models were fitted without constant term predicting SNS by the growing season temperature sum, by which a slope coefficient per treatment mean was obtained. Then, slope coefficients were obtained from the same field, experimental site and year, by averaging treatment means differing in mowing dates. Consequently, a linear model was fitted for the prediction of these slope coefficients using stepwise weighted regression in which SOM, soil pH, precipitation deficit and winter temperature sum were candidate predictors and the number of treatment means averaged was used as weighing factor.
- (2) Analyses were conducted with the objective to estimate SNS for successive harvests within a growing season and to unravel effects of SNS and CAN-N application rates on herbage N uptake. Separate models were fitted on the full calibration data set and on the subset with data on conditions without N application. Mixed models for SNS estimation were fitted using

Table 2 Descriptive statistics of conditions, soil properties and weather variables of the model calibration and model testing data sets (n = 49 and n = 55, respectively, for a subset of

treatment means from conditions without N application) and for all treatment means (including conditions with and without N application, n = 98 and n = 119, respectively)

Property/variable	Unit	Calibration data set				Test data set			
		Mean	SD	Min	Max	Mean	SD	Min	Max
<i>Treatment means of conditions without N application (subset)</i>									
No. of harvests		2.8	1.3	1	5	3.4	1.7	1	7
Soil N supply	kg ha ⁻¹	159	73	17	353	129	72	15	306
Soil organic matter	g 100 g dry soil ⁻¹	43	7	29	65	48	8	27	64
Soil pH		4.8	0.2	4.3	5.2	4.9	0.3	4.5	6.6
Precipitation deficit	mm	2	49	-94	175	ND			
Growing season mean daily temperature sum	°C	1721	847	458	3217	1510	862	229	3278
Preceding winter mean daily temperature sum	°C	253	73	17	353	335	67	194	454
<i>All treatment means (including conditions with and without N application)</i>									
No. of harvests		2.8	1.4	1	5	3.4	1.7	1	7
CAN-N application	kg ha ⁻¹	85	84	0	260	127	138	0	607
Soil N supply	kg ha ⁻¹	207	97	17	457	183	122	15	562
Soil organic matter	g 100 g dry soil ⁻¹	46	6	29	65	49	9	27	64
Soil pH		4.8	0.2	4.3	5.2	4.9	0.3	4.5	6.6
Precipitation deficit	mm	14	68	-94	175	ND			
Growing season mean daily temperature sum	°C	1734	842	458	3217	1512	865	229	3278
Preceding winter mean daily temperature sum	°C	263	127	100	425	325	58	194	454

SD = standard deviation, ND = not determined, CAN = calcium ammonium nitrate

stepwise linear regression, in which growing season temperature sum and CAN-N application rates were forced predictors, and SOM, soil pH, precipitation deficit, winter temperature sum and squared CAN-N application rate were candidate predictors. If there was a significant correlation between two candidate predictors, only the predictor that correlated the most with SNS was used to avoid potential multicollinearity in the models. Squared CAN-N application rate was included as candidate predictor, as herbage N use efficiencies may decrease at higher N application rates (Prins 1983). An interaction between growing season temperature sum and SOM was allowed for, as it has been shown that air temperature correlates with soil temperature (Parton and Logan 1981), mineralisation rate correlates with soil temperature (Macduff and White 1985) and SOM content correlates with mineralisation rate (Vellinga and André 1999). No constant term was taken up in the models, on the assumption that, at zero degrees growing season

temperature sum, herbage N uptake had started. Means and variances of estimation residuals were analysed by ANOVA using F-probabilities to test whether additional predictors besides SOM decreased the size and variance of the SNS estimation residuals. And to test the hypothesis that SNS is estimated equally in conditions with and without N application, using the test data set.

- (3) Validation of the models obtained in step 2 was done by regressing SNS estimations to observations using the test data set. Therefore, the hypotheses that the estimated intercepts and slopes are equal to 0 and 1, respectively, were tested.

Statistical analyses were done using R (version 3.4.0, R core team 2017) and the *rcorr* function of the R package *Hmisc* (version 4.0–3, Harrell 2017). Model selection for stepwise regression was done based on the lowest Schwarz information criterion (SIC).

Results

Correlations between candidate predictors of SNS

Candidate predictors of SNS per degree growing season mean daily temperature sum did not show significant mutual correlations (Table 3). However, for SNS estimations for conditions without N application, the winter temperature sum correlated significantly with the precipitation deficit ($p < 0.001$, Table 4) and the latter was excluded as a candidate predictor. For SNS estimations of all treatment means (including conditions with and without N application), soil pH and winter temperature sum correlated significantly with SOM and precipitation deficit ($p < 0.001$, Table 4), and, therefore, soil pH and winter temperature sum were excluded as candidate predictors.

Estimation of SNS per degree growing season mean daily temperature sum using soil properties and weather variables, for conditions without N application

Soil organic matter correlated with SNS per degree growing season mean daily temperature sum ($r = 0.54$; $p = 0.001$, Fig. 2, but not with soil pH, winter temperature sum and precipitation deficit (Table 3). Stepwise linear regression analyses revealed an effect of SOM ($p < 0.001$) and a tendency for the winter temperature sum to have an effect ($p = 0.067$) on SNS per degree growing season mean daily temperature sum (Table 5, model 1). Each g of

SOM per 100 g⁻¹ dry soil was estimated to increase SNS by 3.6 kg ha⁻¹ and each °C winter temperature was estimated to decrease SNS by 0.088 kg ha⁻¹, for a growing season with a temperature sum of 3000 °C.

Estimation of growing season SNS using soil properties and weather variables for conditions with and without N applications

For conditions without N application, growing season SNS coincided nearly linearly with the growing season temperature sum ($r = 0.92$, $p < 0.001$, Fig. 3). Stepwise regression analyses resulted in the selection of growing season temperature sum, SOM and an interaction between growing season temperature sum and SOM as predictors of SNS ($p < 0.001$ for all) (Table 5, model 3). Soil pH and winter temperature sum were not selected as predictors of SNS.

For all treatment means (including conditions with and without N application), CAN-N application rate was selected as a predictor for SNS ($p < 0.001$) in addition to growing season temperature sum, SOM and an interaction between growing season temperature sum and SOM (Table 5, model 4). Apparent N recovery (ANR) of CAN-N applications was estimated rather constantly between the studies ($58 \pm 14\%$ SE). Precipitation deficit was not selected as a predictor of SNS.

Each °C growing season temperature sum and each g SOM per 100 g dry soil coincided with an SNS change of 78–90 g ha⁻¹ and 3.6–3.9 kg ha⁻¹, respectively. The models estimated total SNS at 220 and

Table 3 Pearson correlations, coefficients (r) and probabilities (p value) for different parameters of the calibration data set averaged per unique field–experimental site–year combination ($n = 31$), for conditions without N application

		Soil N supply per degree growing season mean daily temperature sum	Soil organic matter	Soil pH	Preceding winter mean daily temperature sum
Soil organic matter	r	0.54			
	p value	0.002			
Soil pH	r	– 0.01	– 0.05		
	p value	0.958	0.782		
Preceding winter mean daily temperature sum	r	– 0.17	0.14	– 0.14	
	p value	0.349	0.450	0.460	
Precipitation deficit	r	– 0.15	– 0.02	– 0.01	0.22
	p value	0.428	0.918	0.953	0.244

Table 4 Pearson correlation coefficients (r) and probabilities (p value) for different parameters of the calibration data set, for conditions without N application and for the full data set (including conditions with and without N application)

		Soil N supply	Growing season mean daily temperature sum	CAN-N application rate	Soil organic matter	Soil pH	Preceding winter mean daily temperature sum
<i>Conditions without N application</i>							
Growing season mean daily temperature sum	r	0.91					
	p value	< 0.001					
Soil organic matter	r	0.18	- 0.03				
	p value	0.006	0.703				
Soil pH	r	- 0.05	0.03		- 0.17		
	p value	0.470	0.646		0.011		
Preceding winter mean daily temperature sum	r	0.03	0.06		0.09	0.03	
	p value	0.707	0.376		0.160	0.710	
Precipitation deficit	r	- 0.03	0.08		- 0.03	- 0.03	- 0.42
	p value	0.673	0.231		0.620	0.690	< 0.001
<i>All treatment means (including conditions with and without N application)</i>							
Growing season mean daily temperature sum	r	0.81					
	p value	< 0.001					
CAN-N application rate	r	0.69	0.28				
	p value	< 0.001	< 0.001				
Soil organic matter	r	0.14	- 0.02	0.01			
	p value	0.001	0.601	0.874			
Soil pH	r	- 0.05	0.04	0.03	- 0.32		
	p value	0.268	0.373	0.528	< 0.001		
Preceding winter mean daily temperature sum	r	- 0.01	0.05	- 0.06	0.11	0.05	
	p value	0.725	0.205	0.171	0.012	0.208	
Precipitation deficit	r	0.05	0.12	0.09	-0.03	- 0.02	- 0.49
	p value	0.200	0.004	0.038	0.536	0.643	< 0.001

CAN = calcium ammonium nitrate

297 kg ha⁻¹ year⁻¹ at SOM contents of 35 and 55 g 100 g dry soil⁻¹ for an average growing season with 3000 °C mean daily temperature sum.

The use of growing season temperature sum and the interaction between growing season temperature sum and SOM, compared to the use of only SOM as a predictor, significantly decreased SNS estimation residuals ($p < 0.001$ both for conditions without N application and conditions with and without N application).

SNS was not predicted differently for conditions without N application compared to those that included N application (Table 5, models 3 and 4, respectively), as means ($p = 0.520$) and variances ($p = 0.881$) of SNS estimation residuals did not differ between the models.

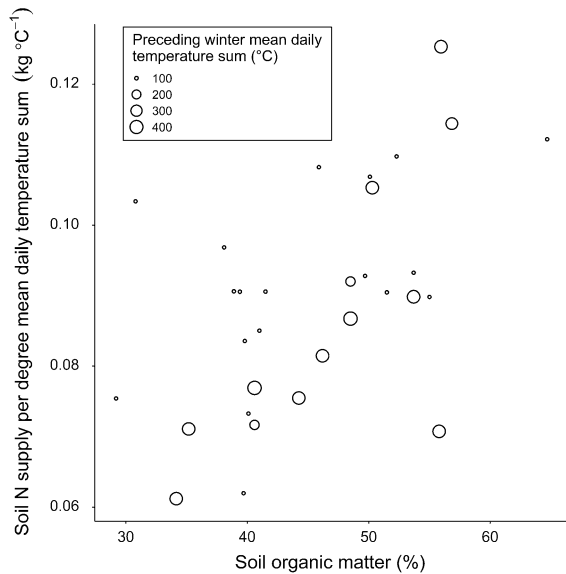


Fig. 2 Annual soil N supply per degree growing season mean daily temperature sum versus soil organic matter content. Sizes of the data points correspond with the variation of the preceding winter (1 December–28 February) mean daily temperature sum

Validation of SNS estimations using the test data set

Models 3 and 4, for conditions without N application compared to those that included N application, respectively, accounted for 78% and 77% of the observed variance and predicted SNS with an RSE of 38.8 and 39.0 kg ha⁻¹. Estimations of SNS on the test data were consistent for experimental site G (Zegveld) but not for E (Wilnis) (Table 6). For experimental site E, measured SNS was on average 24% to 39% higher than predicted ($p < 0.001$ for conditions with and without N application), while for experimental site G, observations were in line with the estimations ($p \geq 0.146$). Compared to all other experimental sites included in the current work, observed mean SNS was markedly higher at experimental site E (339 kg ha⁻¹ versus 259 kg ha⁻¹ at 3000 °C growing season temperature sum). Nevertheless, SOM and growing season temperature sum explained 87% to 88% of the observed variation in SNS at this site (Table 6).

Discussion

Soil properties and weather variables associated with SNS

The hypothesis that SNS can be more accurately estimated by soil properties and weather variables, compared to using only soil properties, was confirmed since growing season temperature sum next to SOM as predictors of SNS significantly decreased estimation residuals.

The observed strong positive correlation between growing season temperature sum and SNS was likely the result of a positive correlation between air temperature and soil temperature (Parton and Logan 1981), a positive correlation between soil temperature and mineralisation rate (Macduff and White 1985) and of the phenomenon that morphological developments of grasses are closely related to the sum of mean daily temperatures (Frank et al. 1985).

The observed positive correlation between SOM and SNS is in line with earlier results from studies on mineral soils (Hassink 1995; Van Eekeren et al. 2010) and peat soils (Vellinga and André 1999). A higher soil SOM content is likely to result in a higher SNS since organic soil N is the main source for SNS, and, C:N ratios of dairy grasslands on peat soils are rather constant (Deru et al. 2019). Moreover, the positive interaction between growing season temperature sum and SOM as a predictor of SNS (Table 5, models 3 and 4) indicates that soils with a higher SOM content are more prone to an increase in SNS at relatively higher growing season temperatures, compared to soils with a lower SOM content. Therefore, in the short term, increased growing season temperatures, e.g. as a result of climate change, may increase SNS for peat soils, especially on soils with a higher SOM content.

The found tendency for an impact of the winter temperature on the annual SNS in the following growing season might have been related to freeze–thaw events. Winters with a lower mean temperature, on average, had more or longer periods of frost than winters with a higher mean temperature (data not shown). Matzner and Borken (2008) showed that, for mineral soils, freeze–thaw events may induce gaseous and/or solute losses of N from soils, on an annual scale. They argued that freeze–thaw events induce changes in microbial biomass and populations, root turnover and soil structure. For agricultural peat soils,

Table 5 Fitted models for the estimation of annual soil N supply per degree growing season mean daily temperature sum ($\text{kg } ^\circ\text{C}^{-1} \text{ ha}^{-1}$, model 1) or growing season soil N supply (kg ha^{-1} , models 2–4)

Model no.	1	2	3	4
Regressor	Soil N supply per degree growing season mean daily temperature sum	Soil N supply	Soil N supply	Soil N supply
Predictor 1	< intercept >	Growing season mean daily temperature sum	Growing season mean daily temperature sum	Growing season mean daily temperature sum
Value	3.93×10^{-2}	8.97×10^{-2}	2.80×10^{-2}	2.68×10^{-2}
SE	1.32×10^{-2}	0.11×10^{-2}	0.59×10^{-2}	0.44×10^{-2}
<i>p</i> value	0.006	< 0.001	< 0.001	< 0.001
Predictor 2	Soil organic matter		Soil organic matter	Soil organic matter
Value	1.21×10^{-3}		4.60×10^{-1}	4.91×10^{-1}
SE	0.28×10^{-3}		0.82×10^{-1}	0.58×10^{-1}
<i>p</i> value	< 0.001		< 0.001	< 0.001
Predictor 3	Preceding winter mean daily temperature sum		Growing season mean daily temperature sum \times soil organic matter	Growing season mean daily temperature sum \times soil organic matter
Value	-2.90×10^{-5}		1.15×10^{-3}	1.13×10^{-3}
SE	1.52×10^{-5}		0.14×10^{-3}	0.09×10^{-3}
<i>p</i> value	0.067		< 0.001	< 0.001
Predictor 4				CAN-N application
Value				5.80×10^{-1}
SE				0.14×10^{-1}
<i>p</i> value				< 0.001
RSE	$1.39 \cdot 10^{-2}$	31.6	24.6	26.7

For each predictor, the fitted value, standard error (SE) and *p* value for the hypothesis *value* = 0 is given. Residual standard errors (RSE) for the full models are given

CAN = calcium ammonium nitrate

there are no known reports of freeze–thaw events on annual soil N dynamics, but it seems likely that such events can similarly affect the physical and biological properties of peat soils. On the other hand, the estimated effect of winter temperatures on annual SNS was rather small, and winter temperatures did not correlate with the rate of SNS per degree of the sum of the growing season temperature. Thus, the effect of winter temperature on SNS in the following growing season played only a minor role or may have been overruled by other factors, on an annual scale, in the studies used for the current work.

It is known that soil pH indirectly affects the availability of mineral N from soil mineralisation (Egan et al. 2019; Jarvis et al. 1996; Rashid et al.

2014), although in the current work pH could not be indirectly or directly related to SNS. Soil pH variations (SD 0.2, pH was often measured per field or experimental site) and ranges (4.3–5.2, Table 2) in the used studies for the current work may have been too small to detect any effects of soil pH on SNS.

Although in the current work precipitation deficit was not found to affect SNS, several studies have shown that soil moisture content affects N mineralisation (Macduff and White 1985; Paul et al. 2003; Verloop et al. 2014). Others suggested that water availability can be a limiting factor for herbage growth in poorly drained dairy grasslands on peat soils, due to soil desiccation at the root zone during relatively dry periods (Deru et al. 2019; Schothorst 1982; Van

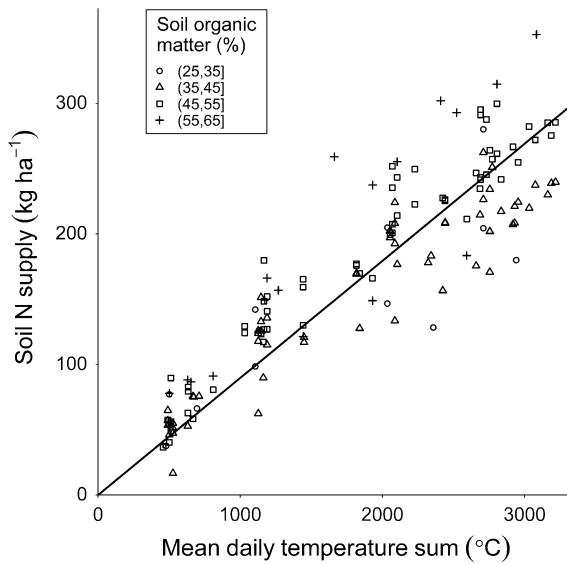


Fig. 3 Growing season soil N supply versus growing season mean daily temperature sum, for conditions without N application. Data points represent measurements per harvest, and shapes represent different soil organic matter classes. Model details of the plotted line are shown in Table 5 (model 2)

Kekem 2004). Strong rainfall events might also affect herbage N uptake by inducing extra soil N losses (i.e. via denitrification or runoff) or affect soil temperatures and thereby the soil microbial community (Jarvis et al. 1996). Possibly, the correlation between soil moisture content and precipitation deficit was low. Besides, since growing season SNS was modelled, short-term relationships between precipitation deficit and SNS could have been compensated for later on in the season (i.e. often short periods of precipitation deficits

Table 6 Linear regression analyses of observed versus predicted soil N supply, for conditions without N application (estimations by model 3) and for all treatment means

N application condition	Experimental site	Intercept			Slope coefficient			RMSD	r ²
		Value	SE	p value	Value	SE	p value		
Without	E	2.42	14.2	0.865	1.35	0.08	< 0.001	75.1	0.87
With and without	E	9.7	9.6	0.314	1.24	0.04	< 0.001	81.4	0.88
Without	G	8.01	4.4	0.070	0.93	0.03	0.015	26.8	0.85
With and without	G	2.36	3.0	0.794	0.98	0.01	0.141	31.0	0.93

The *p* values given are for the hypotheses *intercept* = 0 and *slope* = 1. RMSD = Root mean squared deviations (RMSD) from the estimations in kg ha⁻¹, r² = percentage of variance accounted for by the estimation models. See Table 5 for details of the used estimation models

alternate with periods of surplus during the growing season). Therefore, using actual soil moisture concentrations as predictor and/or performing short period analyses (e.g. per season or harvest) may result in improved SNS estimations.

Estimations of SNS in the current study were in line with other studies carried out in the Netherlands. Vellinga and André (1999) estimated a mean SNS of 252 kg ha⁻¹ year⁻¹ for dairy grassland on peat soils, based on studies carried out over the 1934–1994 period. Van Kekem et al. (2004) estimated mean SNS at 225 kg ha⁻¹ year⁻¹, based on studies carried out over the 1991–2003 period, and argued that mean SNS had slightly decreased since the 1990s due to slight increases in ditchwater levels, compared to levels in earlier decades.

CAN-N application did not affect estimated SNS

The conformation of the hypothesis that the presence and rate of CAN fertilisation does not affect SNS estimations within a growing season was in line with Egan et al. (2019), who found no relationship between herbage ANR of applied ammonium nitrate N (100 kg ha⁻¹ year⁻¹) and soil N mineralisation of an acid sandy soil. On the other hand, studies on mineral soils have shown that inorganic N fertilisation can affect soil N transformation directly or indirectly through the alteration of soil abiotic and biotic characteristics and SOM quality (e.g. Zhang et al. 2012), and therefore possibly also affect soil N mineralisation. Nitrogen fertilisation increases herbage yields and therefore also biomass turnover,

(including conditions with and without N application, estimations by model 4), of the test data set for experimental sites E (Wilnis) and G (Zegveld)

which in turn could also directly increase the SOM content and SNS. However, the soil N content of grassland on peat soils is relatively high ($2.01 \pm 0.46 \text{ g } 100 \text{ g}^{-1}$ dry soil for 20 dairy grassland areas in the western peat area of the Netherlands, Deru et al. 2019) and, in the studies used for the current work, CAN-N application amounts were relatively low ($85 \pm 84 \text{ kg ha}^{-1} \text{ year}^{-1}$ in the calibration data set). Furthermore, since only data of the first year after cessation of organic inputs was used, effects of N fertilisation on SNS of successive years were not included in the current analyses. This might explain the insignificant effect of CAN-N application on soil N mineralisation found in the current work.

Another important factor for the similar SNS estimations under conditions with and without CAN-N applications, was the rather constant estimated annual ANR of CAN-N application between the studies. Estimated mean annual ANR was very similar to the results from Vellinga and André (1999), who found an average ANR of nearly 60% for dairy grasslands on peat soils, based on data of studies carried out in the 1934–1994 period, and somewhat lower than Deru et al. (2019), who reported an average ANR of 65% for 20 dairy grasslands on peat soils for a specific year (2010). This supports the finding that annual ANR of CAN-N application was rather constant within the studied conditions.

From the current work cannot be inferred that other inorganic N fertilisers than CAN do not affect SNS within a growing season, as only studies with CAN fertiliser were used. However, effects on SNS of other inorganic fertilisers, e.g. based on ammonium or urea, applied at similar rates as in the current study, may also be limited due to moment of SNS determination (the first year after cessation of organic and inorganic inputs), the relative short period used for SNS determination (6–7 months) and due to the relative high SOM and organic N content of grassland on peat soils. The latter may overrule, at least within a growing season, effects of inorganic fertiliser types on soil N transformations and stocks.

SNS estimations for the test data set were inconsistent for one experimental site

The estimated SNS for experimental site E was very similar to the mean SNS (342 kg ha^{-1}) found by Sonneveld and Lantinga (2011) for a dairy grassland

on a peat soil with an anthropogenic A horizon receiving relatively high historical organic inputs. According to Van Kekem (2004) and Sonneveld and Lantinga (2011), historical inputs of organic N determine at least about 60% of the annual N mineralisation of dairy grasslands on peat soils. Sonneveld and Lantinga (2011) suggested that the contribution of peat to SNS is lower when an anthropogenic A horizon is present. Soils at site E have an anthropogenic A horizon of 30–40 cm, while at site G, this horizon is not present (Stiboka 1970). Since historical inputs were not recorded at both sites, but were limited to applicable regulations, effects of differences in historical input between sites were not expected but could not be excluded. Furthermore, soil microclimate differences could have affected SNS. Deru et al. (2019) found SNS to correlate with the Ca:Mg ratio and soil air content at pF 2. For mineral soils, Hassink (1994) and Jarvis et al. (1996) suggested that physical (e.g. particles and pores) and biological properties (e.g. the composition and structure of the soil microbial community) may directly and/or indirectly affect soil N mineralisation. Therefore, in order to potentially explain differences in observed and predicted SNS for specific sites, future research on SNS of dairy grassland on peat soils should take into account actual recent historical inputs and parameters characterising the soil microclimate properties (such as temperature, moisture content, C:N ratio, pH, particle and pore size, micro mineral concentrations and ecology).

Conclusions

The current work shows that spatial variation and the temporal increase of growing season soil nitrogen supply can be accurately estimated using growing season degree days and soil organic matter content as predictors. The presented models allow for improved within growing season soil nitrogen supply adapted fertilisation, grazing and harvesting advice. Furthermore, it was found that not only measurements carried out in conditions without but also with calcium ammonium nitrate applications can be used to deduce soil nitrogen supply estimations.

However, the current work also showed that estimated soil nitrogen supply for a specific site was consistently underestimated by the presented models.

To clarify inconsistencies, future research on soil nitrogen supply estimations should take into account actual growing season mean daily temperatures, soil microclimate properties and recent historical inputs.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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