Near infrared technology for soil analysis with implications for precision agriculture

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Introduction

The general goal with the concept of precision agriculture is to apply inputs where they best fill their purpose. Adjustment of inputs are to be made as precisely as possible after what is required by the soil and crop potentials on a high spatial resolution. Consequently, precision agriculture is also often called site-specific agriculture. The yield variations within a field could be considerable: several tons of cereals per ha.[1] Nutrient requirement will vary correspondingly. Thus, site-specific inputs of nutrients will save resources and the impact on the environment could be minimised without lowering total yields or putting product quality at risk.[2]

Regulation of field inputs "on the run" has been made possible by the geographical position system (GPS)-technology, which gives the farmer his exact real time positioning in the field. However, the real challenge is to provide a reliable basis for decision-making. To support high spatial resolution, extensive sampling and analysis is required for many soil and plant characteristics. To be able to regulate the inputs of fertiliser, lime, etc. in relation to soil and crop needs on a high spatial resolution, rational soil analyses strategies are needed. The rapidity, minimal sample preparation requirement and potential for direct field measurements make NIR spectroscopy highly interesting as a future soil sensor.

Together, the contents and quality of clay and organic matter (SOM) in soil regulate or influence most soil properties and processes.[3] Therefore, soil clay and SOM are two parameters with prime interest in soil analyses packages and in precision agriculture. In such agriculture systems they are useful to describe soil-based variations in agricultural fields. However, the analyses do not support adjustments of agricultural practice directly, but are often used in pedotransfer functions.[4] The NIR-spectra has been shown to hold information about both clay[5–10] and SOM.[11–14] However, prediction results are variable and, in most cases, the variation of soil types used has been limited. Recently, promising results have also been published for NIR-based predictions of crop uptake of nitrogen.[15,16]

In this paper the performance of NIR calibrations for clay and SOM matter contents on a large set of samples, covering most of the variation of agricultural mineral soils in Sweden, are tested. In addition the stability of NIR calibrations for N-uptake in winter wheat over years and across fields has been studied.

Table 1. General characteristics of data sets for calibration of *clay* and soil organic matter (*SOM*).

Sample set, country	Sample set type	No. of samples	*SOM* %	*Clay* content %
Ekhaga, SE	2 ha field, grid sampled	52	6.2–14.4	~ 60
Ultuna, SE	Long term field experiment, organic amendments	60	1.7–6.9	~ 40
Askov, DK	Field experiment, N-fertiliser	36	2.1–3.3	~ 11
Jyndevad, DK	Field experiment, N-fertiliser	27	1.5–2.6	~ 4
Ribbingsberg, SE	15 ha field, stratified sampling	33	2.8–4.3	7–26
Swedish farmsites	25 m^2 sample plots	2750	0.9–2	0–70
Danish farmsites	Field experiment areas	50	1.5–4.6	3–22

Experimental

Soil samples

For clay and soil organic matter content (SOM) a sample set of 2750 top soils sampled to represent all Swedish agricultural areas was used (Swedish farmsites). The soils have previously been analysed for numerous properties.[17–19] For clay content all soils where used, but for SOM soils with more than 12% organic matter (7% organic carbon) where excluded. For the SOM studies the Swedish farmsite data were evaluated together with six smaller sample sets: three Danish used by permission of Dr. Ingrid Kaag-Tomsen, Foulum Research Station, DIAS, Denmark, and four Swedish. All seven data sets are described in Table 1.

For crop uptake of mineralised soil N, two adjacent fields (I and II, 10 and 15 ha) were sampled at unfertilised 25 m^2 plots distributed on each field. Field I was sampled in 1997 at 15 plots and in 1998 and 1999 at 20 plots. Field II was sampled in 2000 at 20 plots. The fields are located about 100 km NE of Gothenburg. Winter wheat was cropped all years. The fields were very variable, especially in SOM (Table 2).

Reference methods

Soil texture was analysed with the pipette method according to Gee & Bauder,[20] after the organic matter and carbonates had been removed. The content of clay; < 0.002 mm, silt; 0.002–0.06 mm and

Table 2. Soil organic matter in samples from the unfertilised experimental plots 1997–2000.

Year / Field number	Min %	Max %	Mean %	Median %	St. dev. %
1997 / I	3.1	22.4	8.8	4.8	6.4
1998 / I	2.6	19.4	6.9	5.2	4.8
1999 / I	2.8	17.2	6.7	5.0	5.0
2000 / II	2.2	10.8	4.3	3.6	2.4

sand; 0.06–2 mm was determined. SOM was calculated by multiplying organic carbon with 1.72. Organic carbon was analysed on a LECO CNS 700 after removing the carbonates from the soil samples.

Crop uptake of N was measured as the total N content in above-ground plant parts in August, just before harvest. Four 0.25 m^2 squares were sampled in each plot.

NIR measurements

All soils were air dried and crushed to pass a 2 mm screen before analysis. Every fourth wavelength between 1100 and 2500 nm was recorded on a Bran+Lubbe InfraAlyzer 500.

Data analysis

All data was analysed with Unscrambler 7.6. PLS was used for calibrations and only validation results are shown, either from cross-validation (leave-n-out) or test sets. NIR-spectra were smoothed by second order, seven points, Savitzky–Golay. For clay and SOM calibrations, the first derivative was calculated and for crop uptake of N, baseline corrections were made.

Results and discussion

Clay content

For clay content calibrations 25% of the 2750 samples were left out for validation. The validation result is shown in Figure 1(a). This global model levels off at about 25–30% clay, and there are a number of stray samples. In an attempt to improve performance, six regional models consisting of adjacent districts were also calibrated. For each region 25% of the samples were left out as test sets. This regional classification was accomplished according to three criteria: It should follow existing county borders, it should be represented by at least 200 samples to allow for test set validation and the regions should be as large as possible without loss of model performance. The results are shown in Figure 1(b). This classification significantly improved the results, probably due to smaller variations in soil type. The performance of the regional strategy is probably at the limit of what is possible considering that the error of the reference method is at least 10%. In addition, NIR and the pipette methods do not utilise the same features of the clay minerals. Clay, according to the pipette method, is defined as particles of a size equivalent to a sphere diameter of 2 μm or less. NIR, supposedly, measures the chemically-active surfaces of clay minerals, largely through bound water.[21] The aggregate size distribution, which to a large extent reflect the presence of clay, also influences the spectra.[8] In addition, different clay miner-
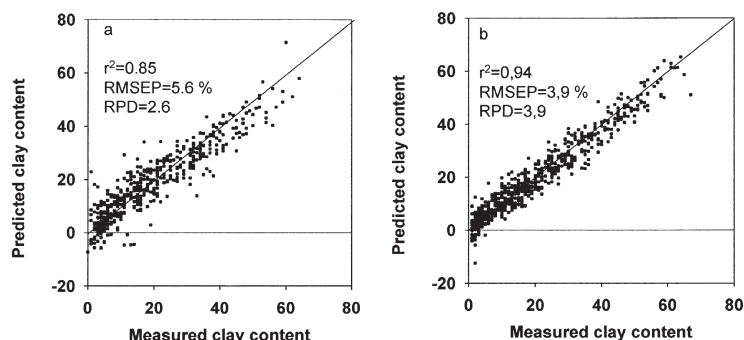

Figure 1. Validation samples for Swedish farmsite data; (a) a global NIR model and (b) six regional NIR models.
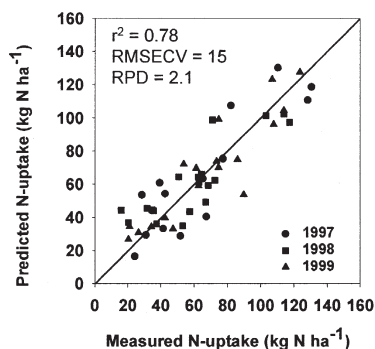
Figure 2. Cross-validation results of NIR predicted vs measured N-uptake in Field I 1997–1999.

als give different spectra,. Thus, soils within the same texture class could have very different spectra depending on geological history, agricultural practice and distribution of particle sizes smaller than 2 μm.

Soil organic matter

A global model (Swedish farmsites) for SOM did not perform satisfactorily (Table 3) and division of the Swedish farmsites set into regional classes as for clay content did not improve the results (data not shown). A comparison of smaller data sets from single fields or field experiments indicated that SOM could be better predicted if the models were restricted to soils with a fairly high clay content or with a limited texture variability (Tables 1 and 3). To test this the Swedish farmsites set was divided into classes depending on clay content: 0–15%, 15–30%, 30–45% and > 45%. As can be seen in Table 4, performance increased with increasing clay content. Especially for the samples with the lowest clay contents, the model was poor. This class made up almost half of the total population. Therefore, this class was subdivided into three classes depending on sand content: 0–30%, 30–60% and > 60%. For the samples with

Table 3. Validated performance of *SOM* calibrations.

Sample set, Country	Validation method	r^2	RMSEP/RMSECV %	RPD
Ekhaga, SE	Leave-one-out	0.92	0.15	8.7
Ultuna, SE	Leave-one-out	0.97	0.14	5.8
Askov, DK	Leave-one-out	0.69	0.09	1.8
Jyndevad, DK	Leave-one-out	0.68	0.09	1.8
Ribbingsberg, SE	Leave-one-out	0.61	0.17	1.6
Swedish farmsites	Test set (25%)	0.46	1.24	1.4
Danish farmsites	Leave-one-out	0.60	0.26	1.5

Table 4. Validated performance of *SOM* calibrations of Swedish farmsites divided in classes after *clay* content. Cross-validation with 50 segments.

Class	N	Range % SOM	r^2	RMSECV %	RPD
0–15 %	1231	0.7–12	0.44	1.3	1.3
15–30%	775	1.6–12	0.80	0.7	2.3
30–45%	408	1.4–12	0.84	0.6	2.5
45–70%	182	2–12	0.86	0.5	3.5

Table 5. N-uptake in over ground plant parts 1997–2000 at time of harvest 1997–2000.

Year/Field no.	Min Kg N ha^{-1}	Max Kg N ha^{-1}	Mean Kg N ha^{-1}	Median Kg N ha^{-1}	St. dev. Kg N ha^{-1}
1997 / I	24.4	130.6	63.6	51.8	35.7
1998 / I	16.1	117.4	61.7	62.8	28.8
1999 / I	20.5	123.5	67.1	68.1	31.7
2000 / II	34.0	103.7	59.0	52.6	22.8

0–30% sand, this procedure improved the results to the level of the most clayey ones (*RMSEP* = 0.41, *RPD* = 3.1), suggesting that the large number of soils with a high sand content in the Swedish farmsites data set disturb the possibilities for good calibrations. The *RMSECV* found for these data sets corresponded well to that which can be found in the literature. However, it is difficult to make a detailed comparison as the variability in soil type and geographical origin usually are smaller than in our investigation.

Crop uptake of nitrogen

The N-uptake in above ground plant parts at the time of harvest was similar in all four years (1997–2000). However, in Field II (2000) the range and variation over the field was smaller (Table 5). This corresponds to the smaller degree of variation of organic carbon in Field II (Table 2). A composite cross-validated NIR model for 1997 to 1999 performed satisfactorily well without shifts between years (Figure 2). N-uptake 1999, predicted by an NIR-model calibrated on 1997–1998 samples, showed a small bias [Figure 3(a)]. A small bias was also evident for a corresponding model using organic carbon as the predictor [Figure 3(b)]. The similar procedure was used to predict the N-uptake in Field II (2000) with models calibrated on Field I (1997–1999) samples (Figure 4). In this case a bias was only seen for the organic carbon based model. The *RMSEP* and *RPD* were also significantly better for the NIR model. This difference between organic carbon and NIR as the predictors supports that the information in the NIR spectra represents a variety of properties of the soil matrix, as suggested by Börjesson *et al.*[15] That the bias generally remains across years is natural, as weather-conditioned differences for crops in different years could not be expected to influence the NIR-spectra.
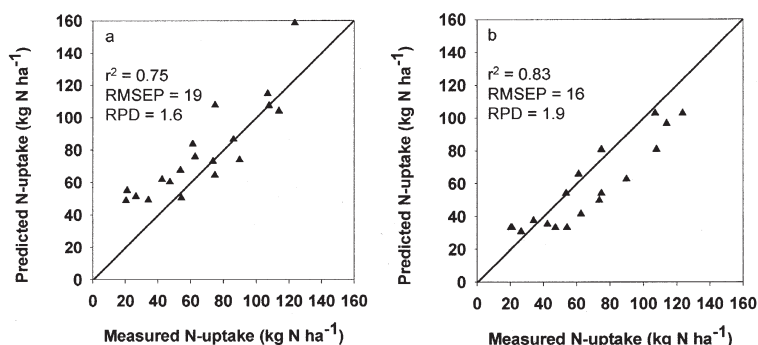

Figure 3. Predicted *vs* measured N-uptake in Field I 1999 by models calibrated on data from Field I 1997–1998. The models were based on (a) NIR spectra and (b) SOM data.
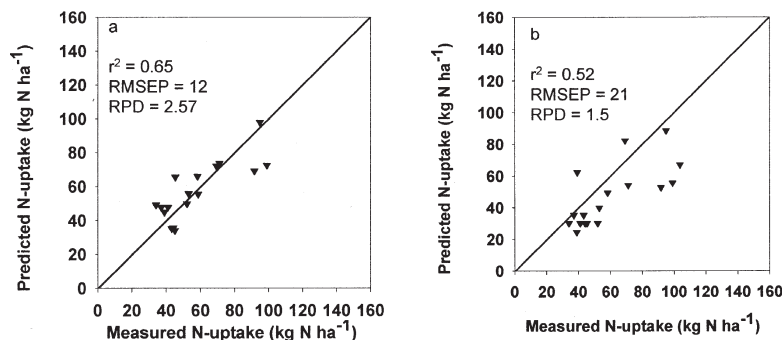
Figure 4. Predicted *vs* measured N-uptake in Field II 2000 by models calibrated on data from Field I 1997–1999. The models were based on (a) NIR spectra and (b) SOM data.

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