

Soil apparent electrical conductivity (EC_a) as a means of monitoring changes in soil inorganic N on heterogeneous morainic soils in SE Norway during two growing seasons

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Abstract

An efficient method to monitor changes in soil inorganic N content during crop growth would be a useful means to guide N fertilization to ensure high yields and low N losses to the environment. In this study, soil apparent electrical conductivity (EC_a) measured by the widely used conductivity meter EM38 was tested as an indirect measurement of available N in spring barley during two cropping seasons at two sites with morainic loam in SE Norway. The experiment was constructed to maximize soil variation. In spite of the 'noise' caused by the soil heterogeneity, concentrations of inorganic N (cN_{inorg}) or NO_3 -N were most strongly correlated with EC_a in both years and at both locations (with one exception). The measurements of EC_a reflected well the temporal variation in inorganic N content (N_{inorg}), and a ranking of the treatments based on EC_a fitted very well with a ranking based on N_{inorg} at the first three sampling times after fertilizing. The best subset of sensor variables (i.e. variables which can be measured 'on-the-go' by sensor techniques in the field) described 27–69% (average 47%) of the variation in topsoil cN_{inorg} . When expanding the regression models to include pH as well, the degree of explanation increased significantly. In conclusion, the method of using EC_a appears to be quite robust in terms of detecting relative differences in cN_{inorg} , whereas a determination of absolute levels of cN_{inorg} with the method is unreliable.

Introduction

Nitrogen is the major determining, limiting nutrient for plant growth. Many nitrogenous compounds are also potential sources of pollution. In cereal production, in-season split application of fertilizer is one way to increase N use efficiency (Lukina et al. 2001). Recent developments in remote sensing, such as measurements of spectral radiance, now offer methods for optimizing such in-season fertilization, based on estimates of plant N uptake (e.g. Stone et al. 1996; Lukina et al.

2001). These methods do not, however, take account of inorganic N already in the soil at the time of split application. An efficient way to monitor spatial and temporal variability of soil inorganic N during crop growth would provide useful information when deciding optimum rates for split application of fertilizer.

The use of sensor techniques provides a time- and cost-effective alternative to traditional soil sampling and laboratory analyses, in order to monitor spatial and temporal soil variation. One sensor-based technique is to measure apparent

electrical conductivity (EC_a) of a soil profile. Three potential pathways of electrical conductivity (EC) exist in soil: (i) Through the liquid phase (via salts contained in soil water), (ii) through the solid phase (soil particles in direct and continuous contact with one another), and (iii) through the solid-liquid phase (primarily via the exchangeable cations associated with clay minerals) (Corwin and Lesch 2003). Hence, numerous soil properties affect EC in soil. If changes in EC_a are mainly caused by one dominating soil property, then EC_a may be calibrated as a direct measurement of that dominant factor (Sudduth et al. 2003).

Three methods have been used to determine EC_a in soil: measurements of electrical resistivity (ER) using the Wenner array, measurements of electrical conductance with time domain reflectometry (TDR), and with non-invasive electromagnetic induction (EM). The former is well suited for precision agriculture applications, because the volume of measurements is large, thus reducing the local-scale variability. The depth of penetration and volume of measurements can be easily adjusted by changing the spacing between the electrodes, but the invasive nature of the resistivity measurements requires good contact between the soil and the four electrodes, and is thus less reliable in dry and stony soils (Corwin and Lesch 2003).

The advantages of TDR are its ability to measure both soil water and EC_a , and possibility of obtaining continuous unattended measurements (Corwin and Lesch 2003). Until recently, the method has involved insertion of metallic rods into the soil at each point of measurement, which has made the method time-consuming and less suited to precision agriculture applications. Inoue et al. (2001) presented, however, some prototypes of TDR probes for 'on-the-go' measurements. A drawback of these is that the zone of measurements is limited to the upper 8–10 cm of the soil.

The electromagnetic induction approach (EM) is an efficient method to obtain measurements with high density over large areas. Other advantages are that a large volume is measured, thus reducing local scale variability (as the ER-method), and that the method is suitable in relatively dry or stony soils, since no contact is necessary between the soil and the EM sensor (Hendrickx et al. 1992). Variation of depth of penetration and volume of measurements may be obtained by lifting the EM-device above the ground, but it is very complicated

to determine the actual subsequent depth and volume of measurement (Corwin and Lesch 2003).

In this paper the EM approach was chosen because of its ability to cope with stony soils and the large volume of measurements obtained by the method. The device selected for the EM-measurements was the Geonics EM38 (Mississauga, ON, Canada; www.geonics.com), which is the EM- EC_a sensor most often used in agricultural applications (Sudduth et al. 2001). The device has an intercoil spacing of 1 m and may be operated in one of two measurement modes. In vertical mode (coil axes perpendicular to soil surface) the effective measuring depth is approximately 1.5 m, whereas in horizontal mode (coil axes parallel to soil surface) the effective measuring depth is approximately 0.75 m.

EM- EC_a has been used successfully as an indirect indicator of important soil physical and chemical properties, such as soil salinity hazard (Williams and Baker 1982), soil water content (Sheets and Hendrickx 1995; Khakural et al. 1998), clay pan thickness (Doolittle et al. 1994), topsoil thickness (Kitchen et al. 1999), depth of sand deposition (Kitchen et al. 1996) and nutrient levels (Heiniger et al. 2003). Dissolved nutrients, such as NO_3-N , probably affect EC_a more under saturated conditions than when the soil is very dry (Heiniger et al. 2003). Nevertheless, Eigenberg et al. (2002) concluded that EM- EC_a was effective in identifying the dynamic changes in plant available soil N throughout the growing season of silage-corn, i.e. over a range of soil water conditions. They applied 168 kg N ha^{-1} in their mineral fertilizer treatment and up to 273 kg N ha^{-1} as animal manure, and found that the method using EC_a was best suited for the manure treatments, whereas the fertilizer treatment had a lower EC_a and less residual effect after application. Using a portable EC meter, Zhang and Wienhold (2002) found very strong correlation between EC and soil inorganic N at concentrations corresponding to approximately $50\text{--}140 \text{ kg N ha}^{-1}$ in the upper 15 cm, both when measured in the laboratory (1:1 soil water slurry) and when measured *in situ* (i.e. at the site where their soil was collected). Their results thus indicate that there is a potential for using EC_a as an indirect measurement of inorganic N, also at low to moderate N rates. To be of practical interest, the method should be robust with respect to soil heterogeneity, which can be considerable within even relatively short distances.

The objective of this research was to test whether measurements of EM-EC_a can be used to monitor temporal variation in topsoil inorganic N after application of moderate rates of fertilizer N, even when soil variation is significant.

Materials and methods

Changes in EC_a during the growth of barley (*Hordeum vulgare* L., var. 'Ven') was investigated over 2 years (2002 and 2003) in an ongoing field experiment at two sites in central SE Norway, Apelsvoll Research Center and Kise Research Station.

Experimental sites

Apelsvoll Research Center (60°42' N, 10°51' E, 250 m above sea level) is located at the western shore of lake Mjøsa, and has a mean annual precipitation of 600 mm and a mean annual temperature of 3.6 °C and a mean temperature of 12.0 °C in the growing season May–September. The experimental area, which slopes 3–6% eastwards, is on an

imperfectly drained brown earth (Gleyed melanic brunisols, Canada Soil Survey) with dominantly loam and silty sand textures (see Table 1).

Kise Research Station (60°46' N, 10°48' E, 130 m above sea level), is located at the eastern shore of lake Mjøsa, and has a mean annual precipitation of 585 mm and a mean annual temperature of 3.6 °C and a mean temperature of 12.2 °C in the growing season May–September. The experimental area gently undulating, and the soil covers a range from imperfectly drained brown earth (Gleyed melanic brunisols, Canada Soil Survey) to humified peaty gley (Terric Humisol, Canada Soil Survey) (see Table 1).

Precipitation, soil and air temperature for the actual period are shown in Figure 1 for both sites. These data are taken from meteorological stations, located at a distance less than 200 m from the respective experimental areas.

Experimental design

The field trials (10.5 × 160 m) were established in 2001 and consisted of 20 replicate blocks con-

Table 1. Soil properties of the three replicate blocks used in this study at Apelsvoll and Kise, respectively. Means, standard deviations (SD) and range.

Soil properties ^a	Apelsvoll			Kise		
	Mean	SD	Range	Mean	SD	Range
CEC (0–15 cm)	11.2	2.65	6.46–15.8	38.5	17.70	18.3–64.8
Ca (0–15 cm)	6.17	2.75	2.45–10.4	30.6	14.85	13.2–52.4
Mg (0–15 cm)	0.51	0.22	0.21–0.82	1.82	0.41	1.33–2.49
K (0–15 cm)	0.21	0.05	0.11–0.31	0.21	0.09	0.09–0.33
Na (0–15 cm)	0.04	0.01	0.03–0.06	0.10	0.04	0.05–0.19
H (0–15 cm)	4.29	1.60	1.00–5.80	5.82	2.38	2.70–9.40
Ignition loss (0–25 cm)	47.2	22.06	23.4–66.9	146	87.81	77.6–245
Ignition loss (25–60 cm)	50.7	16.19	41.3–69.4	70.1	74.73	17.8–156
Gravel (0–25 cm)	89.0	41.24	53.0–134	62.3	10.79	50.0–70.0
Gravel (25–60 cm)	85.7	29.74	54.0–113	62.7	31.50	31.0–94.0
Sand (0–25 cm)	567	45.09	520–610	417	90.19	330–510
Sand (25–60 cm)	530	65.57	460–590	437	92.38	330–490
Silt (0–25 cm)	300	17.32	280–310	380	60.00	320–440
Silt (25–60 cm)	310	26.46	280–330	413	70.95	350–490
Clay (0–25 cm)	133	32.15	110–170	207	35.12	170–240
Clay (25–60 cm)	163	66.58	90–220	150	30.00	120–180
pH (H ₂ O) (0–15 cm) ^b	5.80	0.200	5.60–6.00	6.55	0.119	6.43–6.66
BD (0–25 cm) ^c	1.30	0.049	1.26–1.35	1.00	0.295	0.66–1.20
BD (25–60 cm) ^c	1.36	0.082	1.29–1.45	1.28	0.384	0.84–1.54

^aUnits: CEC (cation exchange capacity) and exchangeable cations given in cmol_c kg⁻¹, gravel in g kg⁻¹ bulk soil, BD (dry bulk density) in g cm⁻³ dry soil, and other components in g kg⁻¹ fine earth (<2 mm).

^bpH (H₂O) measured in soil samples taken in spring 2002.

^cBD; dry bulk soil density, calculated from texture, depth and ignition loss according to Riley (1996).

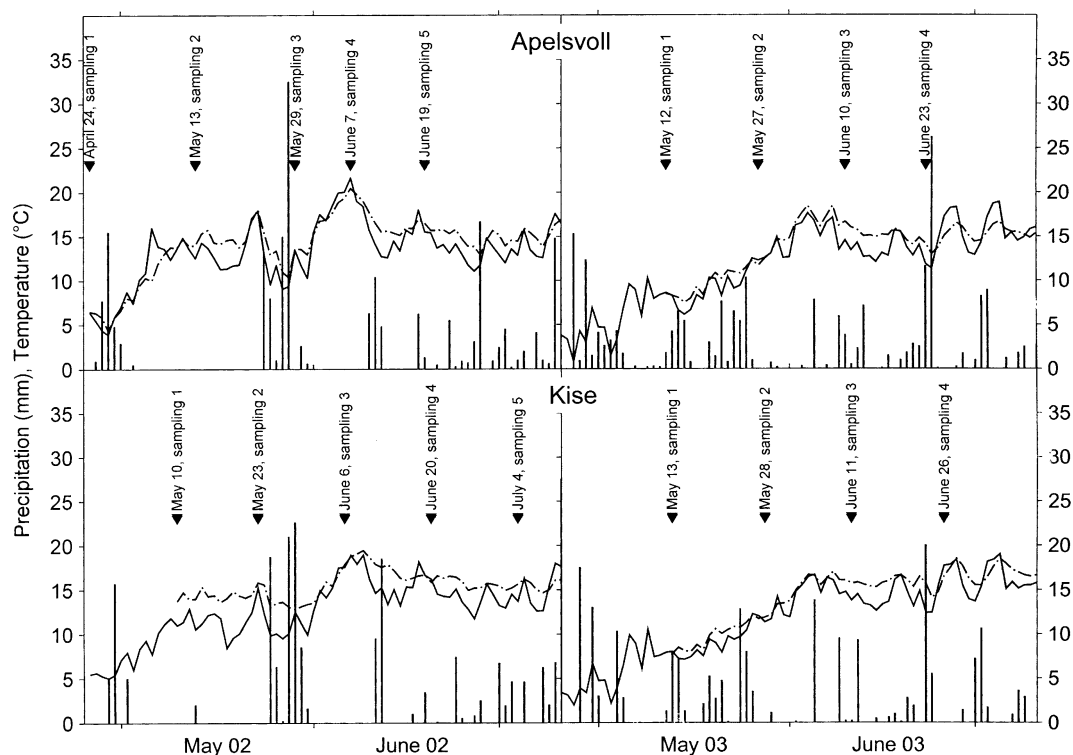


Figure 1. Air temperature (daily average; solid lines), soil temperature at 10 cm (daily average; dash dots) and daily precipitation (bars) at Apelsvoll (above) and Kise (below) during the measuring periods in 2002 and 2003. Times of soil sampling and EC_a measurements (t) are indicated with arrows. Fertilizing and sowing were conducted immediately after the first samplings.

taining seven 1.5×8 m plots with fixed location over both years (Figure 2). The sites were selected so as to maximize soil variation along the trial and to minimize variation within replicate blocks. Five N level treatments were used within each block: 0, 60, 90, 120 and 150 kg N ha^{-1} (designated N0, N60, N90, N120 and N150, respectively), with N given as calcium ammonium nitrate at the time of sowing. Treatments were randomized between the five middle plots each year, while border plots along each side of the trials received 120 kg N ha^{-1} .

P and K were applied before sowing each spring ($21.5 \text{ kg P ha}^{-1}$ and $73.1 \text{ kg K ha}^{-1}$, given as a PK compound fertilizer).

Measurements

At the establishment of the field trials in 2001, soil samples were taken at two depths (0–25 cm and 25–60 cm) from each replicate block by a soil auger (15 mm diameter, 8–12 probes per

sample) and analyzed for particle size and ignition loss. In each of the two field trials the three most contrasting replicate blocks with regard to particle size and ignition loss were selected. During the experiment, soil samples (0–15 cm) were taken shortly before fertilizing/sowing and thereafter at fortnightly intervals (see Figure 1) from all five N treatments in the selected blocks. The soil samples were taken with a soil auger (15 mm diameter) between the rows of barley approximately 0.4 m from the edge of the plots (10 probes per sample taken along the space between rows 3 and 4, Figure 2), and kept frozen until analysis.

Each of the field moist soil samples was split into three sub-samples (40 g). One set was used for gravimetric determination of soil water content. Another set was extracted with 1 N KCl (1:5 w/w), and concentrations of $\text{NO}_3\text{-N}$ ($c\text{NO}_3$) and $\text{NH}_4\text{-N}$ ($c\text{NH}_4$) were determined colorimetrically (Aquatec 5400 Analyzer, Tecator, Sweden). On the third set of sub-samples soil pH (H_2O) and EC was measured (1:2.5 soil to distilled water w/w) with a pH/

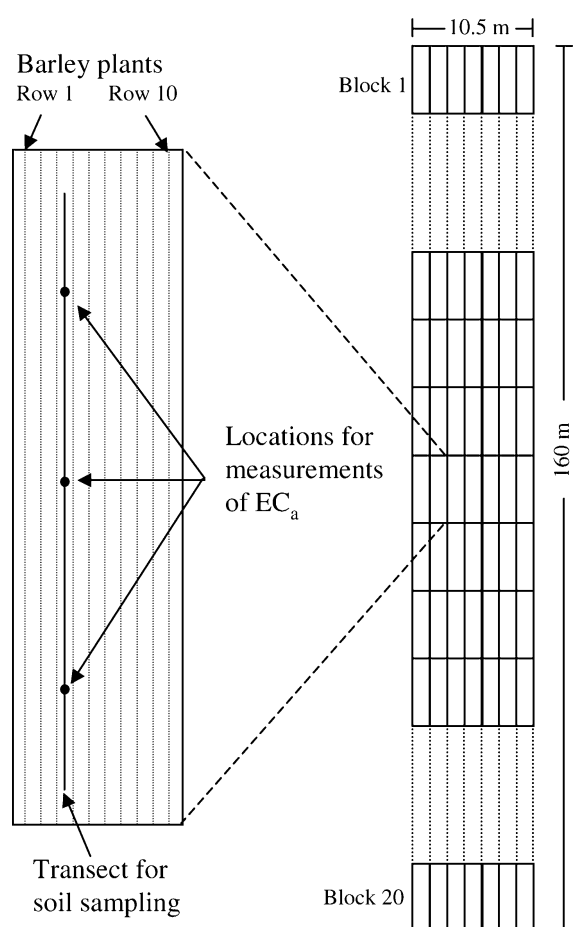


Figure 2. Experimental layout and sampling locations.

EC meter (Horiba D-24 pH/EC System, Spectrum Technologies, INC., US). In addition, the first samples taken in 2003 (prior to sowing/fertilizing) were extracted with 1 M ammonium acetate, and exchangeable Ca^{2+} , K^+ , Mg^{2+} and Na^+ were analyzed spectrometrically (ICAP 1100, Thermo Jarrell Ash Corp, US). Exchangeable H^+ was determined by titration (NaOH) and CEC calculated as the sum of the five cations. At each soil sampling, EC_a was measured on all plots within the selected replicate blocks, using a magnetic dipole soil conductivity meter (EM38, Mississauga, ON, Canada; www.geonics.com). The device was operated manually by placing the device directly on the ground in both horizontal and vertical modes at three points (same location each sampling time) along the same line as where the soil samples were taken (Figure 2). In the following,

measurements of EC_a in horizontal and vertical modes will be denoted EM_H and EM_V , respectively. The zero setting of the device was checked for each 5–10 plots, to minimize any effects of instrumental drift.

Immediately after sowing each year, temperature loggers (Temperature recorder MK III, Temprecord International Ltd., Auckland, New Zealand) were buried at 10 cm depth in each of the selected replicate blocks. Temperature was logged once per hour and daily averages were calculated from these readings.

Data analysis and statistics

The measurements of electrical conductivity were all log-transformed, since they were assumed to be log-normally distributed (Hendrickx et al. 2002). The N concentrations (cN_{inorg} ; $\mu\text{g N } 100 \text{ g}^{-1}$) also appeared to have a log-normal distribution. Therefore, both these data are presented mainly as log-transformed data in tables and figures. Soil inorganic N (N_{inorg} ; kg N ha^{-1}) is also presented. To calculate amounts from concentrations, bulk soil density (BD) was estimated from texture, depth and ignition loss according to Riley (1996). Both N_{inorg} and volumetric water content (θ) were corrected for gravel content in the soil samples.

At sampling time 2 in 2002, three measurements of cN_{inorg} were unreasonable high at both Apelsvoll and Kise (calculated N_{inorg} was 70–150 kg N ha^{-1} higher than that applied). Since this was the first sampling after fertilizing, and there had been only little precipitation, it is possible that some of the soil samples contained particles of un-dissolved fertilizer. These high values were therefore deleted from the dataset.

The statistical software package MINITAB (MINITAB inc. 2000, Release 13.1) was used for basic statistics (correlation), variance analysis (ANOVA) and linear regression analysis (stepwise selection, $\alpha = 0.15$). One-way ANOVA was used to test differences in pH levels between replicate blocks for each site and year separately.

Linear regression models were tested with respect to their ability to predict cN_{inorg} in topsoil during the growing season. As a first step, it was tested whether sensor variables, i.e. variables that could, hypothetically, have been measured 'on-the-go' in the field, could give an adequate description

of the variation in cN_{inorg} , EM_H , EM_V , soil water content and temperature were considered as sensor variables, and the best model was sought. The measurements of EC_a (EM_H and EM_V) were both 'true' sensor variables, whereas soil water content and temperature were considered as hypothetical sensor variables, since 'on-the-go' measurements of these variables are feasible (Mueller et al. 2003). The variables were checked for multicollinearity by calculating the variance inflation factors (VIF). The VIF should not exceed 10 in order to avoid serious problems with multicollinearity (Montgomery and Peck 1992). While there were significant correlations between some of the independent variables, the calculated VIF were all <4.8 , except at Kise in 2003, where the VIF between EM_H and EM_V was 8.6.

As a second step, the variable list was expanded to include pH, to see if it improved the regressions. Although pH cannot be measured 'on-the-go,' commercial sensors exist, which allow rapid *in-situ* pH measurements. The rationale for including pH was that some strong correlations were found between pH and cN_{inorg} (data not shown), and pH differed significantly between treatments at both Apelsvoll and Kise (see Results section).

Results

There were generally strong correlations between EC_a and most of the relatively stable soil properties measured (Table 2). There were, however, clear differences between the locations. At Apelsvoll, EC_a was most strongly correlated with topsoil ignition loss and gravel content, and the content of subsoil silt. At Kise, ignition loss was even more strongly correlated with EC_a , but in contrast to the findings at Apelsvoll, there was very strong negative correlations between EC_a and the subsoil sand and gravel contents, but not with topsoil gravel content. The effects of CEC and exchangeable cations on measured EC_a were more pronounced at Kise than at Apelsvoll, with correlation coefficients ≥ 0.77 for both EM_H and EM_V .

All the variable soil properties were correlated with measured EC_a , but the correlations were not all consistent between years and locations (Table 3). Either cN_{inorg} or cNO_3 was most closely correlated to EM_H in both years and at both locations, except at Kise in 2003, when soil water content correlated most strongly with EM_H . When all data were pooled, the strength of the correlations between EM_H and the variable soil properties decreased in the order: soil

Table 2. Correlation coefficients between selected soil properties and apparent soil electrical conductivity (log-transformed), measured before sowing/fertilizing in spring 2003 with EM38 in either horizontal (EM_H) or vertical (EM_V) modes.

Soil properties ^a	Apelsvoll ($n = 15$)		Kise ($n = 15$)	
	EM_H	EM_V	EM_H	EM_V
EM_H	–	0.95***	–	0.98***
CEC (0–15 cm)	0.29	0.21	0.93***	0.93***
Ca (0–15 cm)	0.66**	0.61*	0.93***	0.94***
Mg (0–15 cm)	0.69**	0.64*	0.80***	0.81***
K (0–15 cm)	–0.05	–0.21	0.84***	0.83***
Na (0–15 cm)	0.73**	0.66**	0.77**	0.77**
H (0–15 cm)	–0.76**	–0.79***	0.91***	0.91***
Ignition loss (0–25 cm)	0.81***	0.72**	0.87***	0.89***
Ignition loss (25–60 cm)	0.68**	0.68**	0.83***	0.85***
Gravel (0–25 cm)	–0.80***	–0.71**	–0.28	–0.24
Gravel (25–60 cm)	–0.35	–0.22	–0.96***	–0.97***
Sand (0–25 cm)	–0.42	–0.47	–0.66**	–0.63*
Sand (25–60 cm)	–0.34	–0.21	–0.15	–0.11
Silt (0–25 cm)	0.04	0.08	0.61*	0.58*
Silt (25–60 cm)	–0.75**	–0.72**	–0.20	–0.24
Clay (0–25 cm)	0.61*	0.62*	0.67**	0.64*
Clay (25–60 cm)	0.57*	0.44	0.61*	0.58*

^aSee Table 1.

Significant at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3. Correlation coefficients between apparent soil electrical conductivity (log-transformed), measured with EM38 in either horizontal (EM_H) or vertical (EM_V) mode, and selected soil characteristics measured during the cropping seasons 2002 and 2003.

Soil properties	Apelsvoll		Kise		All data
	2002 (n = 70)	2003 (n = 60)	2002 (n = 75)	2003 (n = 60)	2002–03 (n = 265)
EM _H					
EM _V	0.85***	0.84***	0.87***	0.94***	0.89***
cNO ₃ ^a	0.46***	0.64***	0.77***	0.57***	0.61***
cNH ₄ ^b	0.39**	0.64***	0.57***	0.44***	0.36***
cN _{inorg} ^c	0.45***	0.65***	0.76***	0.58***	0.57***
θ ^d	0.31**	0.52***	0.57***	0.79***	0.69***
Temp ^e	0.33**	0.39**	−0.29*	0.25	0.13*
pH (H ₂ O)	−0.05	−0.15	−0.68***	−0.54***	0.05
EC ^f	0.20	0.51***	0.42***	0.36**	0.54***
EM _V					
cNO ₃	0.23	0.37**	0.52***	0.53***	0.45***
cNH ₄	0.21	0.31*	0.40***	0.39**	0.24***
cN _{inorg}	0.23	0.34**	0.51***	0.53***	0.41***
θ	0.22	0.27*	0.66***	0.72***	0.65***
Temp	0.30*	0.28*	−0.37**	0.43**	0.07
pH (H ₂ O)	0.04	0.09	−0.66***	−0.55***	0.03
EC	−0.02	0.26*	0.39**	0.23	0.42***

^aLog-transformed NO₃-N concentrations.

^bLog-transformed NH₄-N concentrations.

^cLog-transformed concentrations of inorganic N.

^dVolumetric water content.

^eDaily average soil temperature at 10 cm depth.

^fElectrical conductivity measured in 1:2.5 soil-to-water extracts.

Significant at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

water content > cNO₃ > cN_{inorg} (cNO₃ + cNH₄) > electrical conductivity (EC_{1:2.5}) > cNH₄ > soil temperature (10 cm depth). For the pooled data, pH was not significantly correlated to EM_H (nor to EM_V). At Kise, however, pH was strongly negatively correlated with both EM_H and EM_V. There was no correlation between pH and EC_a at Apelsvoll. ANOVA showed significant differences ($p < 0.008$) in pH levels between replicate blocks at both locations and in both years.

Soil temperature and EM_H was significantly correlated at both locations and in both years, except at Kise in 2003, where EM_V but not EM_H was correlated with soil temperature. Interestingly, soil temperature was negatively correlated with both EM_H and EM_V at Kise in 2002, whereas it was otherwise positively correlated.

Measurements of EC_a made with EM38 in horizontal (EM_H) and vertical (EM_V) modes were strongly correlated. For the total data set, there was an overall tendency that the EM_H-measurements were more strongly correlated to the measured stable soil properties than were the

EM_V-measurements (exceptions here were subsoil ignition loss and clay content, Table 2). At Kise, there were only minor differences between the measurements modes, and no such tendency could be observed (Table 2). For the variable soil properties measured throughout the experimental period, EM_H was the superior method at both Apelsvoll and Kise (Table 3). With a few exceptions at Kise (soil temperature and soil water content in 2002 and pH in 2003), measurements of EM_H correlated more strongly with all properties in both years than did EM_V. Hence, in the following most attention will be paid to the former.

When analysing the data at the treatment level, positive correlations between EM_H and (log-transformed) concentrations of inorganic N were established at both locations for all treatments (except for the zero-treatment at Apelsvoll, Table 4, Figure 3). The correlations tended to increase with increasing fertilizer level up to N90, above which there was no apparent improvement. The strength of the correlations was roughly the

Table 4. Correlation coefficient between log-transformed N-concentrations and apparent soil electrical conductivity (log-transformed), measured with EM38 in horizontal (EM_H) position, for each treatment.

N fraction ^a	N0	N60	N90	N120	N150
<i>Apelsvoll (n = 26)</i>					
cNO ₃	-0.04	0.41*	0.69***	0.62**	0.67***
cNH ₄	0.01	0.48*	0.63**	0.59**	0.62**
cN _{inorg}	-0.02	0.49*	0.69***	0.64***	0.68***
<i>Kise (n = 27)</i>					
cNO ₃	0.45*	0.67***	0.74***	0.84***	0.70***
cNH ₄	0.30	0.54**	0.63***	0.63***	0.47*
cN _{inorg}	0.44*	0.67***	0.75***	0.84***	0.69***
<i>All data (n = 53)</i>					
cNO ₃	0.35*	0.57***	0.67***	0.73***	0.68***
cNH ₄	0.03	0.33*	0.39**	0.39**	0.37**
cN _{inorg}	0.34*	0.55***	0.61***	0.66***	0.62***

^aSee Table 3 for explanation of variables.

Significant at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

same for the two inorganic N fractions at Apelsvoll, whereas at Kise, EM_H correlated in most cases more strongly with cNO₃ than with cNH₄. When the data from both locations was pooled, this phenomenon was even more pronounced.

There were large differences in topsoil inorganic N content between the sampling times throughout the growing season, at both Apelsvoll and at Kise (Figure 4). Most N_{inorg} was measured at sampling time 2, for all treatments at both locations and in both years (the average over years is shown in Figure 4). As the growing season proceeded, there was a gradual decline in N_{inorg} until the last sampling. Before fertilization the content of N_{inorg} at Kise was on average about three times that at Apelsvoll (sampling time 1, Figure 4). At all later samplings, however, the level of inorganic N was about 20–70% higher at Apelsvoll than at Kise. The proportion of cNO₃ was on average 0.57 (SE = 0.197) and 0.75 (SE = 0.172) of cN_{inorg} at Apelsvoll and Kise, respectively (data not shown).

Measured EM_H was roughly 50% higher at Kise than at Apelsvoll, probably due to the higher average water content throughout the growing season (74% higher) at Kise than at Apelsvoll (Figure 4). The pattern of N_{inorg}, with an initial increase in N content from sampling time 1–2, followed by a decline from sampling 2 onwards, was also seen for the EM_H-measurements at Kise. At Apelsvoll, EM_H increased until sampling time 3, whereafter a decline

was observed. At sampling time 5 the range of measured EM_H was quite large at Apelsvoll compared to that of N_{inorg}, which was at the same level for all treatments at this sampling. At sampling time 2 and 3 a ranking of the treatments based on measured EM_H was identical to a ranking based on measured N_{inorg}. The only exception was N150 at Kise, which had the highest EM_H at sampling time 3, but the second highest N_{inorg}.

The best subsets of sensor variables described between 27 and 69% of the variation in topsoil cN_{inorg} (Table 5). EM_H explained most of the variation in cN_{inorg} of all the sensor variables, followed by EM_V. Soil water content and temperature were weakly related to cN_{inorg} and were thus only sometimes included in the regression models.

When the regression models were expanded to include pH, the degree of explanation for the total data set increased from 42 to 59%, and the variation between locations and years was reduced (Table 5). Looking at both years together, the degree of explanation was about the same at Apelsvoll and Kise. After EM_H, pH was the most important predictor of cN_{inorg}.

Discussion

Apparent electrical conductivity (EC_a) shows the depth-weighted summarized effect of all factors influencing EC in soil. When using EC_a as an indicator for one particular soil property, the effect of the other properties may be considered as ‘noise’ (Sudduth et al. 2003). In this experiment all properties but topsoil inorganic N concentration (cN_{inorg}) were considered as ‘noise,’ and the latter was deliberately maximised by selecting the three most dissimilar replicate blocks, in terms of particle size and ignition loss, at each site (see Table 1). The rationale for this was to see whether measurements of EC_a could be used to monitor changes in cN_{inorg} during crop growth in spite of marked soil variation, which is the rule rather than the exception in Norwegian agricultural fields.

‘Noise’ from relatively stable soil properties

The results showed that the constructed soil heterogeneity affected EC_a significantly. EC_a correlated

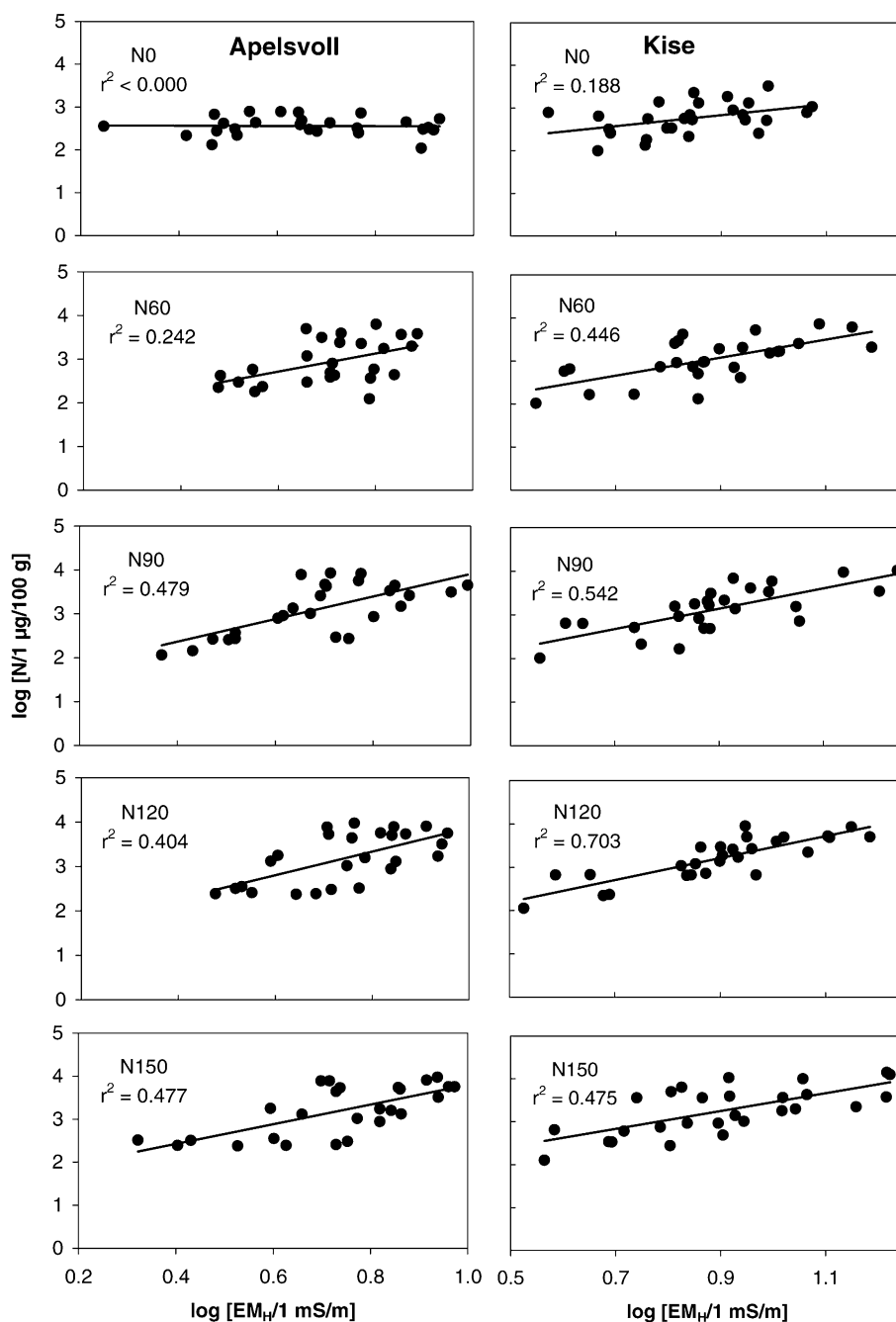


Figure 3. Apparent electrical conductivity measured with EM38 in horizontal mode (EM_H) and log-transformed inorganic N concentrations for treatments 0, 60, 90, 120 and 150 N at Apelsvoll (plots to the left) and Kise (plots to the right) in 2002 and 2003. Lines indicate linear trends.

strongly with particle size (Table 2, both locations), and the variation in exchangeable cations was also well reflected by the measurements. These results fit well with the established knowledge for non-saline

soils, where EC_a is primarily a function of soil texture, CEC and moisture content (Sudduth et al. 2001). Ignition loss appeared to be even more positively related with EC_a than was soil texture.

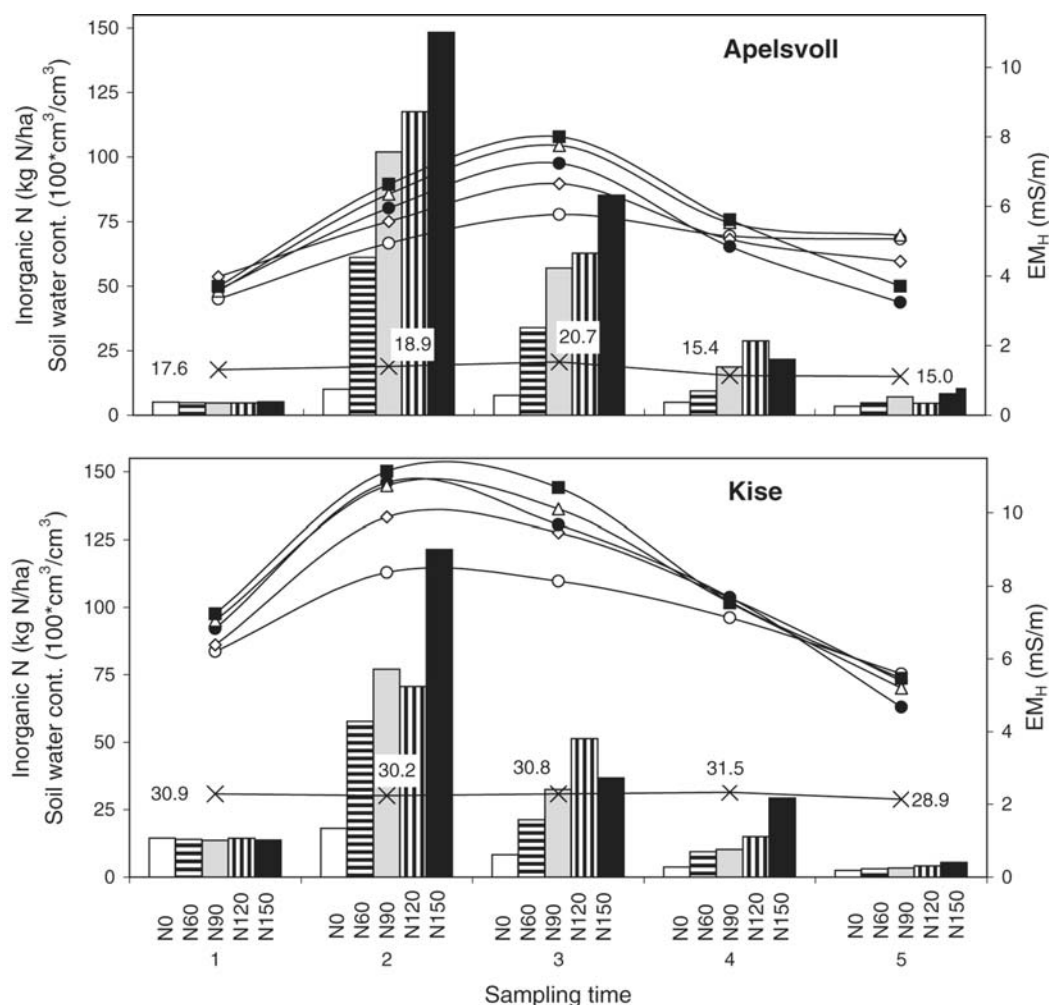


Figure 4. Inorganic N content (bars), volumetric water content (averaged over treatments and years, \times), and EM_H for N0 ($-\circ-$), N60 ($-\diamond-$), N90 ($-\bullet-$), N120 ($-\triangle-$) and N150 ($-\blacksquare-$) during the growing season (averaged over 2002 and 2003) at Apelsvoll (upper plot) and at Kise (lower plot). There were only 4 sampling times in 2003. Sampling times are given in Figure 1.

This confirms earlier findings on the same soil type (Korsaeth 2004). Rhoades et al. (1989) identified the volumetric content of soil particles (θ_{soil}) as one of six major factors influencing EC_a . The θ_{soil} factor is influenced primarily by the texture and bulk density of the soil (Rhoades and Corwin 1990), while the latter is strongly negatively correlated with ignition loss (Riley 1996). Sudduth et al. (2003), who measured EC_a in claypan soils in Missouri and Illinois, USA, reported strong and positive correlation between EC_a and organic C on the Illinois field ($r = 0.62$, EC_a measured by the ER-method), but they found negative correlation coefficients on the two Missouri fields (-0.5 to -0.7 , measured by EM38 (EM-method) and Veris

3100 (ER-method), which both gave roughly the same results). The authors did not discuss these contrasting findings. There were, however, some differences in the soil properties between the sites, which may explain some of the divergence. The soil with the positive correlation (Illinois field) contained 21–54 $g\ kg^{-1}$ less clay and 2.2–2.5 $g\ kg^{-1}$ more organic C than the two soils with negative correlation (Missouri fields). The organic C content was thus 33–39% higher, and its variation was also much larger (0.17–0.19 larger CV) compared with the Missouri fields. Experiences in Norway have shown that ignition loss and EC_a may be strongly positive related when the soil organic matter (SOM) content is high and the clay content is low, but not

Table 5. Sequentially adjusted coefficients of determination ($\text{adj-}R^2$) for linear regression models with topsoil inorganic N (log-transformed concentrations) as dependent variable and other measurements conducted during the cropping seasons as predictors.

Predictors ^a	All data	Apelsvoll			Kise		
		2002	2003	2002–2003	2002	2003	2002–2003
<i>Sensor variables^b</i>							
log EM _H	32.2	19.4	41.1	29.6	56.5	32.6	47.8
log EM _V	4.0	7.9	13.7	4.6	8.7	–	5.4
θ	3.1	– ^c	–	–	1.1	–	2.6
Soil temperature	2.2	–	3.1	–	2.2	–	1.7
<i>Total adj-R^2</i>	41.5	27.3	57.9	34.2	68.5	32.6	57.5
<i>Sensor variables and pH</i>							
log EM _H	32.2	8.3	41.1	29.6	56.5	32.6	47.4
log EM _V	8.0	1.8	3.9	7.6	8.7	–	5.1
θ	–	17.5	–	0.5	3.3	–	1.9
Soil temperature	–	–	–	–	0.4	1.6	–
pH (H ₂ O)	18.8	39.4	21.6	23.9	10.1	7.3	6.3
<i>Total adj-R^2</i>	59.0	67.0	66.6	61.6	79.0	41.5	60.7

^aSee Table 3 for explanation of variables.

^bSensor variables; variables which could have been measured ‘on-the-go’ by sensor techniques in the field.

^cNot included in the regression model by the stepwise procedure since $\alpha > 0.15$.

when SOM content is low and clay content is high (Korsaeth 2004).

‘Noise’ from variable soil properties other than cN_{inorg}

The more variable soil properties measured during the cropping seasons also represented a considerable source of ‘noise.’ At both sites, the variation in soil water content particularly affected EC_a. Since the liquid phase is one of three pathways for electrical conductivity in soil (Corwin and Lesch 2003), a strong correlation between θ and EC_a was expected, and the results are in agreement with numerous other reports (e.g. Sheets and Hendrickx 1995; Khakural et al. 1998; Eigenberg et al. 2002; Sudduth et al. 2003).

The soil water content appeared to affect EC_a to a larger extent at Kise than at Apelsvoll. This may be related to the fact that the water content at Kise was higher than at Apelsvoll. Moreover, the presence of areas with humified peaty gley among the brown earth at Kise, certainly increased the variation in soil hydrological parameters (e.g. infiltration rate, water holding capacity) between the replicate blocks.

Soil temperature has been found to correlate positively with EC to such a degree that tem-

perature conversion factors have been developed (e.g. Sheets and Hendrickx 1995; Corwin and Lesch 2003). In order to assess the actual effect of temperature in the current study, the EC_a measurements were not corrected. At Kise there was a negative correlation between soil temperature and EC_a in 2002. That particular year there were relatively small variation in soil temperatures between sampling times, but the replicate block dominated by humified peaty gley had significantly lower temperature at each sampling time compared with the other two replicate blocks (data not shown), possibly due to higher heat capacity. Lower temperature should normally result in lower EC_a, but this was probably more than overcome by the positive effect of larger content of soil organic matter in this replicate block. In 2003 the differences in soil temperature between the replicate blocks at Kise were for some reason smaller, but the differences between sampling times were larger (data not shown). The contrasting effect of low temperature and high content of soil organic matter in the one replicate block was thus less important for the results. Mueller et al. (2003) also suggested that other soil properties (e.g. soil particle size) masked the effect of soil temperature on EC_a in their experiment. Sudduth et al. (2001) found that seasonal soil moisture differences had

approximately twice the effect on EC_a than differences in soil temperature.

At Kise, pH and EC_a were strongly negatively correlated in both years, but EC_a was not affected by pH at Apelsvoll (Table 3). The negative correlation between EC_a and pH at Kise corresponded well with the strong and positive correlation between EC_a and exchangeable H^+ (Table 2), whereas at Apelsvoll such a pattern was not found (EC_a and pH were not significantly correlated but EC_a and exchangeable H^+ were positively correlated). Heininger et al. (2003) also reported a negative relation between EC_a and pH. It appears, however, that the direct effect of pH on EC_a may be masked by other soil properties (as was the soil temperature). Clay et al. (2001) could establish positive relations between EC_a and pH. They related this to salt removal from summit soils and accumulation in footslope soils. Increased pH in footslope soils thus coincided with higher salt concentrations and increased water content, both of which are factors that increase EC_a .

The correlation coefficient between EM_H and $EC_{1:2.5}$ ranged from 0.36 to 0.42, except at Apelsvoll in 2002 (no significant relation). This is slightly below the values reported by Eigenberg and Nienaber (1998) ($r = 0.45$). They did not, however, mention at which soil/water ratio they measured EC. Since the proportion of the soil phases (liquid/solid) is influenced by the extract ratio, the EC is affected by this ratio. A very strong correlation between EC_a and standard laboratory EC measurements of topsoil is, however, unlikely, not only because of the effect of different moisture content between the soil *in situ* and the soil extract prepared for EC measurements, but also since the measurements with EM38 represent a much deeper horizon than that of the soil samples.

Measurements of EC_a and changes in soil inorganic N

The content of N_{inorg} in spring was larger at Kise than at Apelsvoll. This is reasonable considering the higher average ignition loss at Kise (see Table 1), which implies a larger potential for N mineralized from soil organic matter. In spite of this, the level of N_{inorg} was considerably higher at Apelsvoll throughout the experiment, particularly

at sampling times 2 and 3 (Figure 4). It is commonly considered that growing plants represent the main sink for N_{inorg} , as found by Korsæth et al. (2002) under comparable conditions. Plant N uptake should thus explain most of the decline in N_{inorg} from sampling time 2 onwards. If the fertilizer was more slowly dissolved at Apelsvoll, as hypothesised above, then the plant N uptake would also be delayed, since undissolved fertilizer is unavailable. Delayed N uptake in plants at Apelsvoll could thus explain the higher levels of N_{inorg} at Apelsvoll at sampling times 2 and 3 compared to those at Kise. Higher denitrification at Kise would in theory give the same result. The soil water content was on average 74% higher at Kise than at Apelsvoll, but θ did not exceed 32 vol%, which equals water filled pore space well below 70%. Water filled pore space below 70–80% implies that denitrification would be low (Maag 1995). Moreover, the proportion of NO_3 -N in the topsoil was larger at Kise than at Apelsvoll, which also indicates that the reductive transformation of NO_3 -N was of little importance here.

In spite of the 'noise' caused by the variation in the relatively stable soil properties, cN_{inorg} was fairly strongly correlated with EC_a at both locations and in both years, with correlation coefficients for cNO_3 in the range of 0.5–0.8 for EM_H and 0.2–0.5 for EM_V (Table 3). In comparison, Eigenberg and Nienaber (1998) reported a correlation coefficient of 0.4 between EM_H and cNO_3 in a 4-year field study with applications of fertilizer, manure and compost (manure and compost at rates matching either the recommended N- or P-rate). Their treatments did not, however, include zero-plots, which, when included, normally improve the correlations. On the other hand, their soil samples were collected to reflect the response function of EM_H , by selecting soil volumes in proportion to the expected response from the soil section (e.g. larger volumes from the topsoil due to larger relative response). The experiment was continued, and in a later report (Eigenberg et al. 2002) results from measurements during the growth of silage maize during 1999 was presented. For the fertilizer treatment (168 kg N ha⁻¹ applied) they found no correlation between EM_H and cNO_3 in the 0–23 cm layer, but a strong correlation ($r = 0.60$) in the layer below (23–46 cm). Since Eigenberg et al. (2002) conducted measurements over a much longer period (March–November)

than in the current study, it is to be expected that leaching of inorganic N has played a more important role in their study.

The positive relation between EM_H and cN_{inorg} was also observed at the N treatment level (only partly for the zero-treatment, Table 4, Figure 3). The poorer correlation between EM_H and the inorganic N fractions for the zero treatment compared to the others, may be explained by lower variation in cN_{inorg} during the measurement periods, due to the absence of fertilizer input. There was no apparent effect on the correlations when increasing the N-input above 90 kg N ha^{-1} . The results show that the presented method of monitoring variations in plant available N during crop growth is quite robust at fertilizer levels commonly used for cereals in Norway, which are generally larger than 100 kg N ha^{-1} .

At Kise, there was a tendency that cNO_3 was more strongly correlated with EM_H than was cNH_4 , whereas at Apelsvoll the strength of the correlations was roughly the same for both N fractions. This corresponds well with the observed differences in the relative proportion of nitrate to ammonium at the two locations (larger proportion of NO_3 -N at Kise). Eigenberg and Nienaber (1998) found a significant correlation between EM_H and cNO_3 , but not for cNH_4 . On average, they measured more than twice as much NO_3 -N as NH_4 -N in the soil. Since EM_H is a measure of the total (weighted) conductivity in soil, it is likely that variation of ions with high concentration would have a larger effect on the conductivity than that of ions low in concentration.

Measurements of EM_H made during the growth of spring barley reflected well the temporal variation in N_{inorg} (Figure 4), with an initial increase after fertilizer application followed by a decrease later on. Eigenberg et al. (2002) also demonstrated that fertilizer application resulted in a temporary rise in the level of EC_a (also measured as EM_H). In their experiment, however, other factors than cN_{inorg} appeared to have a stronger influence on the temporal fluctuations of EM_H in the same time of year as in the present study (April–June). The main reason for this was probably relatively large amounts of precipitation during the measurement period. They concluded that their fertilizer treatment had a lower EC_a and less residual effect than did treatments with manure and compost, which were also tested in their experiment.

There was a tendency at Apelsvoll for the peak in measured EM_H (sampling time 3) to be delayed compared to the peak in N_{inorg} (sampling time 2). This may partly be explained by the increase in soil water content from sampling time 2–3 (Figure 4, upper plot). The phenomenon was observed in both years (data not shown). Another explanation for the observed delay could be that the fertilizer was not completely dissolved at sampling time 2 at Apelsvoll, due to much lower soil water content than at Kise (Figure 4). Preliminary tests showed that the effect of undissolved compound fertilizer on EC_a is low compared to that of dissolved fertilizer. This is to be expected from the higher mobility, and thus better distribution when the nutrient ions are in the water phase. Another factor pointing in the direction of undissolved fertilizer at sampling time 2, was that six observations of N_{inorg} at sampling time 2 in 2002, had to be removed due to unreasonably high levels (see Materials and methods). Although three of these observations were made at Kise, the largest levels were measured at Apelsvoll (data not shown).

The ranking of the treatments based on EM_H fitted very well with a ranking based on N_{inorg} at sampling 2–4. Considering the large degree of soil variation deliberately included in the experiment through its design, and the relatively small differences between the treatments (30 kg N ha^{-1}), these results underline the potential of EM_H as a tool to monitor changes in N_{inorg} during the cropping season.

Time and cost effective determination of inorganic N in topsoil

The attempt to estimate topsoil N_{inorg} by means of sensor variables (EM_H , EM_V) and hypothetical sensor variables (soil temperature and water content) was only partly successful. Up to 69% of the variation in cN_{inorg} could be accounted for (at Kise in 2002, Table 5), but the variation between years and locations was large. Using EM_H as a predictor alone was in some cases as good as including all the sensor variables. Including EM_V as a second predictor resulted in a 4–14% units increase of the adjusted R^2 , but the attempt to reduce the ‘noise’ by including soil temperature and water content to the regressions, had hardly any effect at all.

Inclusion of pH improved all the regressions (Table 5). The relatively large effect of pH is most likely a result of the experimental design, which deliberately maximised the soil variation. This variation could partly be seen as significant differences in pH levels between the replicate blocks at both locations. The improvement achieved by pH in the regressions was greatest at Apelsvoll, where the differences in pH between replicate blocks were largest (data not shown). It may thus be concluded that pH had to be included in the regressions, in order to achieve reasonably robust estimates of cN_{inorg} during crop growth. A justified question is then whether a method which involves *in-situ* measurements of pH, really represents a time and cost effective alternative to traditional methods of determining inorganic N in topsoil. In contrast to the other variables in the regressions, pH cannot be measured 'on-the-go,' and can, therefore, not be considered as a sensor variable. Although equipment for rapid *in-situ* pH analysis is available, the advantage of such an indirect way of estimating cN_{inorg} , compared to e.g. direct measurement in the field with quick tests for nitrate, is questionable.

Differences between EM_H and EM_V

Measured EM_H correlated generally more closely with the topsoil analyses than did EM_V . This is to be expected from the sensitivity functions of EM38 (McNeil 1980), which show that the relative contribution to the signal from the topsoil is larger for EM_H than for EM_V . Other authors have also observed the phenomenon. Khakural et al. (1998) found that A-horizon thickness was best estimated by measurements of EM_H . Boettinger et al. (1997), who used measurements of EC_a to estimate soil depth to a cemented (petrocalcic) subsoil horizon, also concluded that measurements made with horizontal dipole orientation of the EM38 (EM_H) was the best mode. In the present research, there was no indication of better correlation between subsoil properties and EM_V (Table 2), in spite of the larger relative weighting of the EM_V signal from the subsoil compared to that of EM_H .

Conclusions and practical consequences

The use of EC_a appears to be a promising method to monitor changes in cN_{inorg} during crop growth, even on heterogeneous soils. The combination of sensor variables, i.e. variables which may be measured 'on-the-go,' such as EM_H , EM_V and soil water content, offers a time and cost effective alternative to determine changes in inorganic N in topsoil, compared to traditional methods. Large variations in pH may, however, reduce the potential of the method.

Determination of absolute levels of cN_{inorg} is difficult with EC_a , but it appears to be quite a robust method to detect relative differences, both spatially and temporary. To improve the accuracy some soil samples should be taken. A mapping of EC_a prior to such a soil sampling would provide a good aid to find optimal sampling locations and times. This combined approach (i.e. EC_a mapping followed by soil sampling) would offer an excellent support in experiments where the timing of soil sampling is essential, for example when the synchronization of N mineralization and plant N uptake is focused upon (e.g. Korsath et al. 2002). The common method of making fertilizer recommendations based on soil sampling in spring, could also benefit from such an approach. The inorganic N content of agricultural soils in spring is, however, normally low, and the accuracy of the EC_a -approach at such levels needs to be tested further.

When EM38 is used to relate EC_a with topsoil properties, the device should be operated horizontally (EM_H).

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