Electrical conductivity and nitrate concentrations in an Andisol field using time domain reflectometry

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Abstract
Andisols exhibit unique dielectric properties which may affect estimation of electrical conductivity by time domain reflectometry (TDR). We investigated the potential to continuously monitor electrical conductivity (σ_w) and nitrate concentrations of soil solution using TDR in an Andisol field from December of 2007 through August of 2008. Before the field experiment, we investigated the relationship between σ_w, bulk soil electrical conductivity (σ_b), and volumetric water content (θ) for an Andisol and assessed the use of the Hilhorst model to describe the relationship. The obtained σ_w - σ_b - θ relationship was fitted well by the Hilhorst model with the dielectric permittivity of soil at $\sigma_b = 0$, $\varepsilon_0 = 10$. In the field experiment, σ_w values estimated using TDR with the Hilhorst model were in agreement with those obtained from solution samplers. In addition, a linear regression between σ_w and nitrate concentrations showed positive correlation. The combination of this regression with the σ_w estimated from TDR measurement and Hilhorst model will provide a useful tool for monitoring soil nitrate concentrations in Andisol fields under transient conditions.

Key Words
Time domain reflectometry (TDR), Andisol, nitrate concentrations, soil solution, electrical conductivity

Introduction
Contamination of groundwater by excess fertiliser is a common problem in upland field areas in Japan. To establish sustainable agricultural practices, it is important to estimate the displacement of water and solutes that will occur at a depth below the plant root zone during a given time period. Time domain reflectometry (TDR) has become an established and reliable means to determine volumetric water content (θ) and bulk soil electrical conductivity (σ_b) (e.g. Noborio 2001). As TDR can measure both θ and σ_b in the same soil volume rapidly, it has been used to monitor solutes. Some researchers have applied TDR to estimate nitrate concentrations (Nissen *et al.* 1998; Das *et al.* 1999; De Neve *et al.* 2000). Although Andisols exhibit unique dielectric properties which may affect the estimation of electrical conductivity by TDR, available works evaluating the use of TDR for studying solute transport are still limited (Vogeler *et al.* 1996; Muñoz-Carpena *et al.* 2005). Moreover, little information is available on comparing soil solution electrical conductivity (σ_w) based on TDR measurement with that obtained by conventional methods, soil coring or solution samplers under field transient state conditions. The main objective of this study was to test the applicability of TDR measurements for assessing the temporal dynamics of nitrate concentrations in Andisol fields. To this end, we evaluated a new model to describe the σ_w - σ_b - θ relationship for Andisol. We also conducted a field experiment to compare σ_w based on TDR measurement with that obtained by conventional methods. In addition, we obtained a regression for predicting nitrate concentrations from the σ_w values.

Methods
The σ_w - σ_b - θ relationship model developed by Hilhorst
Hilhorst (2000) developed a novel method for estimating σ_w directly from the measurements of the dielectric permittivity of soil, ε_a, and the bulk electric conductivity of soil, σ_b.

$$\sigma_w = \frac{\varepsilon_p \sigma_b}{\varepsilon_a - \varepsilon_0} \tag{1}$$

ε_p is the dielectric permittivity of soil solution ($\cong 81$), and ε_0 is the dielectric permittivity of soil at $\sigma_b = 0$. For a capacitance sensor, values between 1.9 and 7.6 have been reported for ε_0 (Hilhorst 2000).

Calibration experiment
Soil samples were obtained at the surface and at a depth of 0.6 m from the experimental field. The samples were washed by three pore volumes of distilled water. They were then air-dried, passed through a 2-mm sieve and packed as uniformly as possible into an acrylic cylinder (62.8 mm in diameter and 130 mm high)

up to a height of 110 mm high. ε_a and σ_b were measured using a TDR cable tester (Tektronix 1502B). For all measurements, we used the same three-rod TDR probe (3 mm in diameter and 100 mm long with a 15 mm in space between the centre and outside rods). The TDR probe was inserted vertically into the soil columns. Waveform analysis was conducted using the WinTDR waveform analysis software (Or *et al.* 1997), which enables automated TDR control, data acquisition, and waveform analysis. Water contents were measured by weighing the soil samples gravimetrically using an electronic balance. σ_w was obtained by centrifuging the soil samples at 6000 rpm for 30 min and measuring the electrical conductivity of the supernatant with a conductivity metre.

Field experiment

A field experiment was conducted from 17 December, 2007 to 31 August, 2008 at the National Institute of Rural Engineering in Tsukuba, Japan. The type of soil at this site is Andisol (Typic hydrudand). The soil's physical and chemical properties are listed in Table 1. The soil profile was divided into two layers, a surface layer and a subsurface layer at a depth of 0.4 m. The experimental field was 10 × 10 m in size. The experimental field was fertilised with 200 kg N/ha, 87 kg P/ha and 166 kg K/ha as chemical fertiliser on 25 December, 2007. The ground surface was kept unplanted during the field experiment.

Three-rod TDR probes (5 mm in diameter and 300 mm long with a 25 mm in space between the centre and outside rods) were horizontally installed into pit faces at three locations, at three depths (0.2 m, 0.4 m and 0.6 m). The TDR probes were connected to a cable tester (Tektronix 1502B) through a multiplexer (SDMX50, Campbell Scientific). A copper-constantin thermocouple was installed at a central pit at three depths to compensate for soil temperature when measuring σ_b. Two porous cups were buried at three depths same as the TDR between each pit to collect soil solution samples. ε_a, σ_b and soil temperature data were recorded every hour throughout the field experimental period. The soil solution was sampled one to three times a month during the field experiment.

Table 1. Physical and chemical properties of soils taken from the experimental site.

	Bulk density (g/cm^3)	*Ks* (mm/h)	pH[*1]	T-C (%)	T-N (%)	CEC[*2] (cmol kg^{-1})
Topsoil	0.71	126	6.2	4.3	0.4	22.2
Subsoil	0.63	108	6.3	2.0	0.4	17.4

*1 soil:solution ＝ 5g:25mL

*2 Wada (1986)

Results

Calibration experiment

The TDR-measured σ_b is plotted against σ_w as measured by a conductivity meter on the extracted solution (Figure 1). The results show that a linear relationship exists between σ_b and σ_w in the range of 0.5 to about 3.0 dS/m at each θ. In addition, the data for topsoil and subsoil are similarly. These results may indicate that the σ_w - σ_b - θ relationships are not sensitive to the bulk density. Results from fitting the experimental data to the Hilhorst model are also given in Figure 1. The calculated σ_w - σ_b - θ relationships agree well with the experimental data. In the Hilhorst model, ε_0 is the only parameter calculated from the relationship between σ_b and ε_a. The value of ε_0 was 10 in this study. Ochiai and Noborio (2003) used $\varepsilon_0 = 9$ for σ_w calculations from TDR-measured σ_b and ε_a in an Andisol field. The ε_0 values for the Andisols in Japan are likely to fall around 10.

Field experiment

The σ_w value estimated using TDR with the Hilhorst model was similar to that obtained from solution samples with porous cups (Figure 2). A distinct breakthrough 0.2 m deep was observed in both measured and estimated σ_w values. However, solute transport was detected earlier with TDR than with the porous cups. At a depth of 0.4 m, TDR estimates exhibited similar magnitude and pattern as those for solution samples with porous cups. A gradually increasing σ_w at a depth of 0.6 m from mid-April to mid-May was detected with both TDR and porous cups. In contrast, the σ_w estimated by TDR did not correspond well with the σ_w measured by porous cups after mid-May. The scatter plots show the potential of using σ_w combined with site-specific regressions for predicting the soil nitrate concentrations, which are relatively well correlated to changes in σ_w (Figure 3). The regressions are similar to those reported in previous works. In particular, the regression is close to that obtained from a field calibration experiment by Das *et al.* (1999).

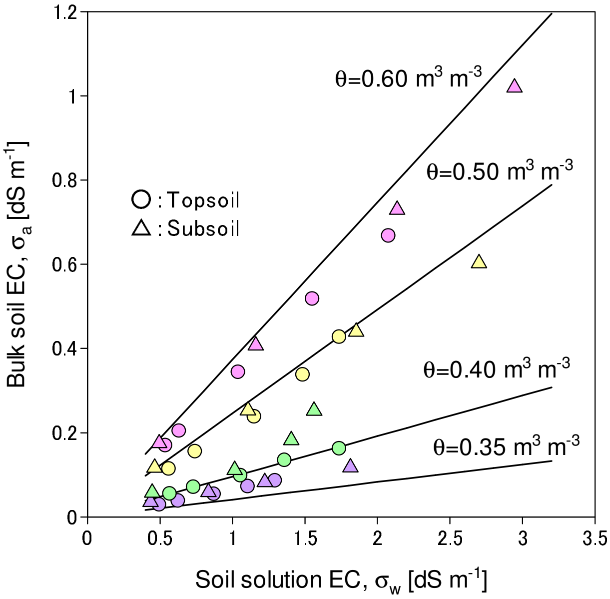

Figure 1. TDR-measured bulk soil electrical conductivity vs. electrical conductivity of the soil solution measured with a conductivity meter for different water contents of an Andisol. Solid lines are prediction of the Hilhorst model using ε_{0} =10.

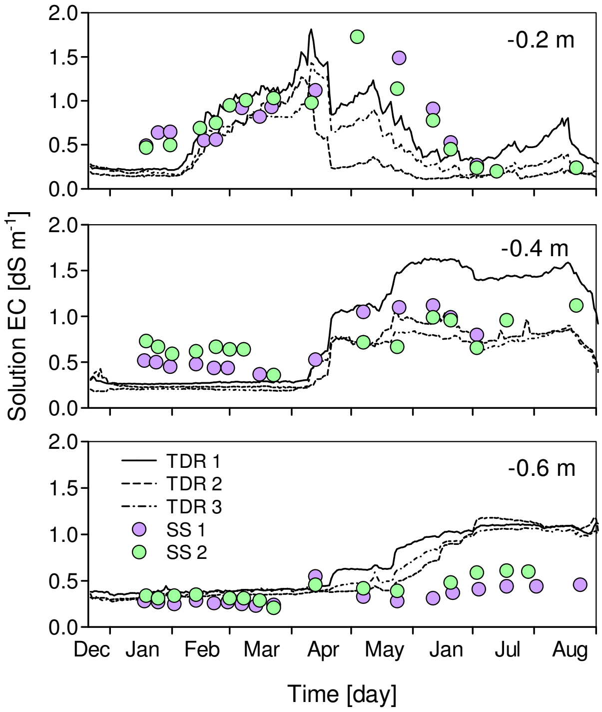

Figure 2. Electrical conductivity of soil solution (σ_w) at 25 °C calculated from TDR measurements compared with values obtained from soil solution extracted with porous cups (SS 1 and SS 2).

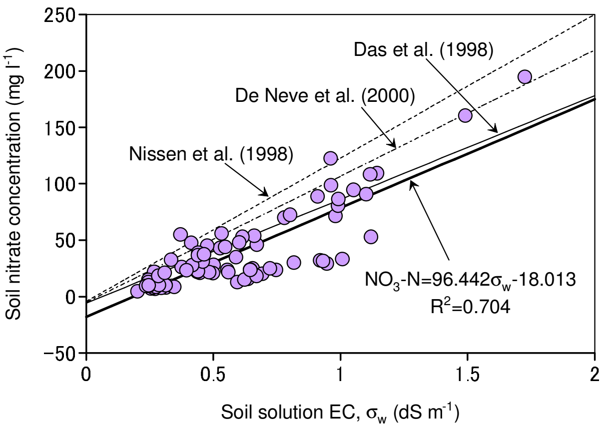

Figure 3. Scatter plots of soil nitrate concentrations as a function of soil solution electrical conductivity. Linear regressions obtained in previous studies are also shown.

Conclusion

Andisols differ from the other soils in their dielectric properties, affecting the estimation of electrical conductivity by TDR. Therefore, we investigated the σ_w - σ_b - θ relationship for Andisols and assessed the use of the Hilhorst model to describe the relationship. The obtained σ_w - σ_b - θ relationship agreed well with the Hilhorst model with $\varepsilon_0 = 10$. In a field experiment, σ_w values estimated using TDR with the Hilhorst model were in agreement with those obtained from solution samplers. In addition, a linear regression between σ_w and nitrate concentrations showed positive correlation. The combination of this regression with the σ_w estimated from TDR measurement and the Hilhorst model will provide a useful tool for monitoring soil nitrate concentrations in Andisol fields under transient conditions.

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