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Monitoring Electrical Conductivity and Nitrate Concentrations in an Andisol Field Using Time Domain Reflectometry

Teruhito MIYAMOTO*, Koji KAMEYAMA and Yukiyoshi IWATA

Agricultural Environment Engineering Research Division, National Institute for Rural Engineering, NARO (Tsukuba, Ibaraki 305-8609, Japan)

Abstract

To establish sustainable agricultural practices, monitoring soil water and solute distributions in actual field conditions is important. Because the estimation of electrical conductivity (EC) using time domain reflectometry (TDR) is considered to be affected by Andisols because of their unique dielectric properties, in this study, we investigate the potential for the continuous monitoring of EC and nitrate concentrations using TDR in an Andisol field. The study was performed from December 2007 to August 2008. To estimate soil solution EC (EC_w), the relationship among EC_w, apparent EC (EC_a) and volumetric water content (θ) for an Andisol was investigated, and three models (Rhoades model, Extended Rhoades model and Hilhorst model) were applied to describe this relationship. The Rhoades model was found to be reasonably accurate in describing the EC_w-EC_a-θ relationship, while the Hilhorst model showed reasonable agreement with the experimental data. In the field experiment, EC_w values estimated using TDR with the Rhoades model correlated with those obtained from solution samples and a linear regression between EC_w and soil nitrate concentrations was obtained from the field experimental data. The use of this regression with EC_w estimated from TDR measurements, together with the Rhoades model, is considered a useful tool for the continuous monitoring of soil nitrate concentrations in Andisol fields under transient conditions.

Discipline: Agricultural engineering
Additional key words: soil physics, solute transport

Introduction

The contamination of groundwater due to the leaching of excess fertilizer is a common problem in upland field areas of Japan. To establish sustainable agricultural practices, estimating the displacement of water and solutes that occur at a depth below the plant root zone during a given period is important. Time domain reflectometry (TDR) has become an established and reliable means to determine the volumetric water content (θ) and apparent electrical conductivity (EC_a) (e.g. Noborio, 2001). TDR can rapidly measure both θ and EC_a in the same soil volume and has hence been used to monitor solutes. In addition, some researchers have applied TDR to estimate nitrate concentrations in soil solutions (Nissen et al. 1998, Das et al. 1999, De Neve et al. 2000). Although Andisols exhibit unique dielectric properties that may affect the estimation of electrical conductivity (EC) when using TDR, their implications for soil EC determination have received little attention. Accordingly, few works are available to evaluate the use of TDR for studying solute transport (Vogeler et al. 1996, Muñoz-Carpena et al. 2005). Furthermore, very little information is available to compare values of soil solution EC (EC_w) based on TDR measurements with values obtained using conventional methods, i.e. soil coring or solution samplers under field transient conditions (Heimovaara et al. 1995, Caron et al. 1999). Accordingly, the main objective of this study was to test the applicability of TDR measurements in assessing the temporal dynamics of EC and nitrate concentrations in Andisol fields. To this end, we evaluated three models (Rhoades et al. 1976, Rhoades et al. 1989, Hilhorst 2000) to determine their efficiency in describing the EC_w-EC_a-θ relationship for Andisols. We also performed a field experiment to compare EC_w based on TDR measurements with those obtained from solution samplers. In addition, we obtained regression to predict nitrate concentrations from EC_w values.

* Corresponding author: e-mail teruhito@affrc.go.jp
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Theoretical background

Rhoades et al. (1976) presented a simple conceptual model relating EC_a and EC_w as follows:

$$EC_a = T\theta EC_W + EC_S \quad (1)$$

where T is interpreted as the soil-specific transmission coefficient to account for changes in tortuosity within the electrical current flow path in relation to changes in soil wetness, and ECs is the surface conductivity of soil particles. The transmission coefficient is often characterized as a function of θ, i.e. $T(\theta) = a\theta + b$, with a and b being constants for a given soil (Rhoades et al. 1976). Although this model appeals in its simplicity for many practical applications, it delivers a curvilinear relationship between EC_a and EC_w at a low range of EC_w (Shainberg et al. 1980).

When EC_w is less than 2-4 dS m^{-1}, Rhoades et al. (1989) extended their former conceptual model to account for mobile, continuous and immobile, discontinuous aqueous phases, and also allowed for different parallel and series solid-liquid conducting pathways. They referred to three conducting paths acting in parallel: (1) alternating layers of series-coupled solid-liquid pathways, (2) solid element pathways and (3) continuous liquid element pathways. They claimed that the contribution of the solid element pathway is negligible because the soil structure does not allow sufficient direct particle-to-particle contact, and thus proposed a simplified two-pathway model (the Extended Rhoades model) as follows:

$$EC_a = \left[\frac{(\theta_s + \theta_{ws})^2 EC_{ws} EC_s}{\theta_s EC_{ws} + \theta_{ws} EC_s} \right] + (\theta - \theta_{ws}) EC_{wc} \quad (2)$$

where EC_{ws} and EC_{wc} are the specific electrical conductivities of the soil water in a series-coupling with solid particles and separate continuous conductance elements, respectively, and θ_s and θ_{ws} are the volumetric fractions of the solid phase and the volumetric water content of the series-coupled solid-liquid element, respectively.

Hilhorst (2000) developed a novel method for direct estimation of EC_w from measurements of the dielectric permittivity of soil, ε_a and EC_a, as follows:

$$EC_w = \frac{\varepsilon_p EC_a}{\varepsilon_a - \varepsilon_0} \quad (3)$$

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

Materials and Methods

1. Calibration experiment

Soil samples were obtained from an experimental field at the National Institute for Rural Engineering in Tsukuba, Japan. The soil at this site is an Andisol (Typic hydrudand); its physical and chemical properties are listed in Table 1. The soil profile was divided into two layers: surface and subsurface layers at a depth of 0.5 m, hence the soil samples were obtained from the surface and a depth of 0.6 m. The samples were washed with three pore volumes of distilled water, air-dried and then passed through a 2-mm sieve.

The EC_w-EC_a-θ relationships were examined on 40 hand-packed soil columns, with four levels of θ at 0.35, 0.40, 0.50 and 0.60 m^3 m^{-3} and six levels of KCl solutions at 0.5, 1.0, 2.0, 3.0, 4.0 and 7.0 dS m^{-1} for topsoil, and with four levels of θ at 0.35, 0.40, 0.50 and 0.60 m^3 m^{-3} and four levels of KCl solutions at 1.0, 3.0, 5.0 and 7.0 dS m^{-1} for subsoil. Each soil sample was 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. ε_a and EC_a were measured using a TDR cable tester (Tektronix 1502B). For all measurements, the same three-rod TDR probe (3 mm in diameter and 100 mm long with a 15 mm space between the center and outer rods) was used, and this was inserted vertically into the soil column. Waveform analysis was performed using the WinTDR waveform analysis software (Or et al. 1997), which allows automated TDR control, data acquisition and waveform analysis. Using an electronic balance, θ was measured by weighing the soil samples gravimetrically, and the relationship between ε_a and θ was obtained by fitting the experimental data as follows:

$$\theta = -0.4 \times 10^{-4} \varepsilon_a^2 + 1.05 \times 10^{-2} \varepsilon_a + 2.34 \times 10^{-1} \quad (4)$$

Soil solution was obtained by centrifuging the soil sample at 6000 rpm for 30 min to measure EC_w. The EC of the soil solution was then measured using the EC metre.

The obtained EC_w-EC_a-θ relationship was fitted using three models (Eqs. (1)-(3)). To estimate the parameters for each of the models, the nonlinear least-squares optimization was applied. For Eq. (2), following Rhoades et al. (1989), the EC_w was estimated assuming $EC_{ws} = EC_{wc}$ ($=EC_w$).

2. Field experiment

A field experiment was performed from 17 December, 2007 to 31 August, 2008. The experimental field measured 10 × 10 m. On 25 December, 2007, the field was fertilized with a compound fertilizer (200 kg N/ha, 87 kg P/ha and 166 kg K/ha), and the ground surface was then maintained in an unplanted condition throughout the field experiment.

Three-rod TDR probes (3 mm in diameter and 100 mm long with 15 mm space between the center and outer rods)

Table 1. Physical and chemical properties of soils obtained at the experimental site

	Bulk density (g cm^{-3})	K_s*1 (mm h^{-1})	$pH(H_2O)$*2	T-C*3 (%)	T-N*4 (%)	CEC*5 (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 Saturated hydraulic conductivity
*2 Soil: solution = 5 g:25 mL
*3 Total carbon
*4 Total nitrogen
*5 Cation exchange capacity

were horizontally installed into pit faces at three locations and at three depths (0.2, 0.4 and 0.6 m respectively). The TDR probes were connected to a cable tester (Tektronix 1502B) through a multiplexer (SDMX50, Campbell Scientific). A copper-constantan thermocouple was installed in the central pit at each of the three depths to compensate for the soil temperature when measuring EC_a.

The suction cup apparatus used to sample the soil solution comprised a porous cup attached to a sampling tube, connective tubing, a sample bottle, a manifold for multiple suction cups and a vacuum source. The suction cups were buried at the same three depths at which the TDR probes were buried, but at two separate locations between the three pits. The ε_a, EC_a and soil temperature data were recorded hourly throughout the field experimental period and ε_a values were converted to θ using the calibration function (Eq. (4)) previously obtained for this Andisol. For temperatures other than 25°C, we adjusted the EC_a values for the temperature effect by multiplying them with a temperature correction factor based on previous work by Heimovaara et al. (1995)

$$f_T = \frac{1}{1 + 0.019\,(T - 25)} \tag{5}$$

where T is the soil temperature. The soil solution was sampled once to three times a month during the field experiment by applying suction of 50-70 kPa. To establish site-specific regression for predicting soil nitrate concentrations, EC and nitrate concentrations of the soil solution were measured using an EC metre (Horiba, Twin EC metre B-173) and ion chromatography (Dionex, ICS-1500), respectively.

Results and Discussion

1. Laboratory calibration

The TDR-measured EC_a was plotted against EC_w (which was measured using the EC metre in the extracted solution) (Fig. 1). The results show a linear relationship between EC_a and EC_w from 0.5 to 3.0 dS m^{-1} at each θ. In addition, the data obtained for topsoil and subsoil are similar. These results may indicate that the EC_w-EC_a-θ relationship for an Andisol is insensitive to bulk density.

Results related to fitting the experimental data to the three models (Eqs. (1)-(3)) are also shown in Fig. 1. The EC_w-EC_a-θ relationship determined by both the Rhoades model (Eq. (1)) and the extended Rhoades model (Eq. (2)) correlated well with the experimental data (Table 2). Because of the linear relationship between EC_a and EC_w in a narrow EC_w range (0.5-3.0 dS m^{-1}), the difference between the models was small. Accordingly, a simple Rhoades model is considered sufficiently accurate to describe the EC_w-EC_a-θ relationship for this specific soil with a narrow EC_w range. Muñoz-Carpena et al. (2005) also found that the Rhoades model yielded the best results for predicting EC_w in a volcanic soil.

The EC_w-EC_a-θ relationship calculated by the Hilhorst model (Eq. (3)) also proved reasonable. Within this model, ε_0 was the only parameter calculated from the relationship between EC_a and ε_a, and in this study, the values of ε_0 were found to be 9.5 and 10.5 for topsoil and subsoil, respectively. Ochiai and Noborio (2003) used ε_0 = 9 for EC_w calculations from the TDR-based EC_a and ε_a in an Andisol field. These ε_0 values for Andisols exceed those for other soils (between 1.9 and 7.6) (Hilhorst 2000). In Japan, the ε_0 values for Andisols are likely to be approximately 10.

2. Field water and thermal regime

Fig. 2 shows the temporal changes in the daily-averaged θ and soil temperatures at various depths. θ is observed to remain high from January to mid-April at every depth, which is attributable to the frequent occurrence of minimal rainfall and the scarce evapotranspiration during this period. In contrast, there was a distinct decrease in the values of θ detected from mid-April to mid-May and from the beginning of July to mid-August because of the lack of rainfall during these periods. The soil temperature at depths of 0.2, 0.4 and 0.6 m respectively remained below 10°C

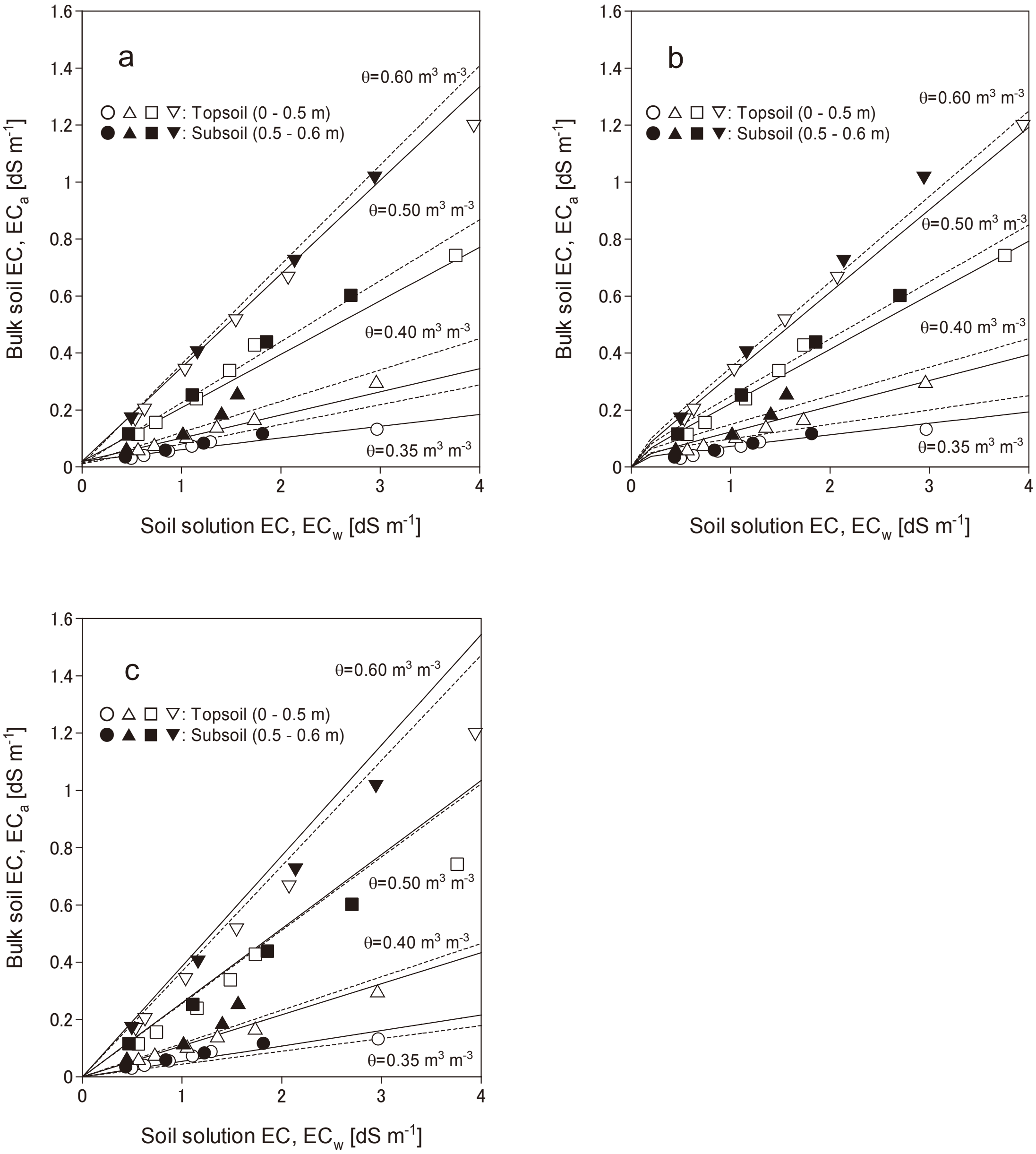

Fig. 1. TDR-measured bulk soil electrical conductivity vs. electrical conductivity of the soil solution measured using an EC metre for different water contents of an Andisol. (a) Rhoades model, (b) Extended Rhoades model and (c) Hilhorst model. The solid and dashed curves are the fitted relationships for topsoil and subsoil, respectively

from December to the end of March, from December to the beginning of April and from December to mid-April, respectively. In addition, the soil temperature at depths of 0.2 and 0.4 m exceeded 20°C from June to August.

3. TDR estimates of field EC_w

EC_w values estimated using TDR with the Rhoades model (Eq. (1)) resembled those obtained from the soil solution samples using the suction cups (Fig. 3) and a distinct breakthrough at a depth of 0.2 m was observed in both measured and estimated EC_w values. However, solute transport detected using TDR was earlier than that using the suction cups. Caron et al. (1999) also reported that tracer movements detected using TDR were earlier than that using suction cups and pointed out that the differences in the tracer movements were probably related to the larger sampling volume used with the TDR than with the suction cups. This volume enabled TDR to detect an early preferential flow because the probes used integrate a larger volume. However, at a depth of 0.4 m, the TDR estimates exhibited a magnitude and pattern resembling that of the solution samples obtained with suction cups. Although

Table 2. Best-fit parameters for the Rhoades, extended Rhoades and Hilhorst models

Model	Parameter	Topsoil	Subsoil
Rhoades model	*a*	1.723	1.540
	b	−0.486	−0.341
	EC_s [dS m^{-1}]	0.020	0.011
	RMSE [dS m^{-1}]	0.033	0.023
Extended Rhoades model	θ_{ws}	0.31	0.30
	θ_s	0.28	0.25
	EC_s [dS m^{-1}]	0.027	0.042
	RMSE [dS m^{-1}]	0.023	0.034
Hilhorst model	ε_0	9.5	10.5
	RMSE [dS m^{-1}]	0.065	0.046

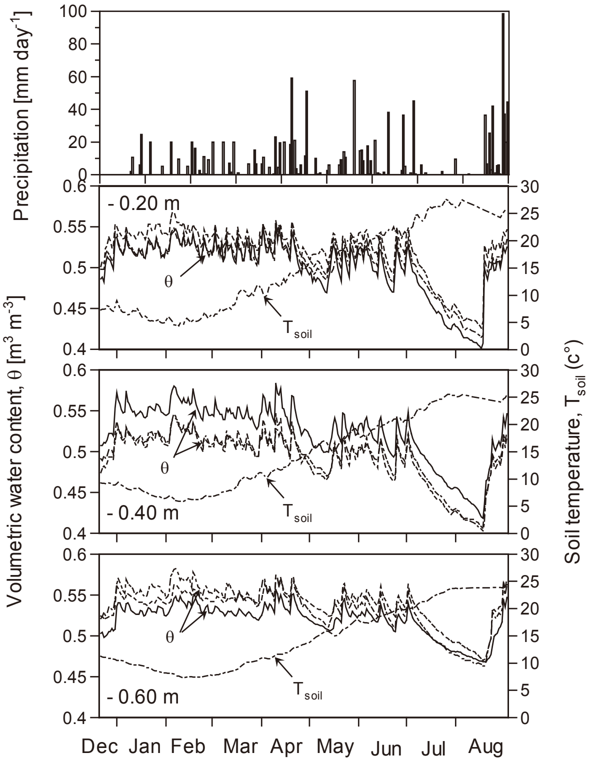

Fig. 2. Volmetric water content measured at depths of 0.2, 0.4 and 0.6 m at three TDR locations, and soil temperatures measured at depths of 0.2, 0.4 and 0.6 m

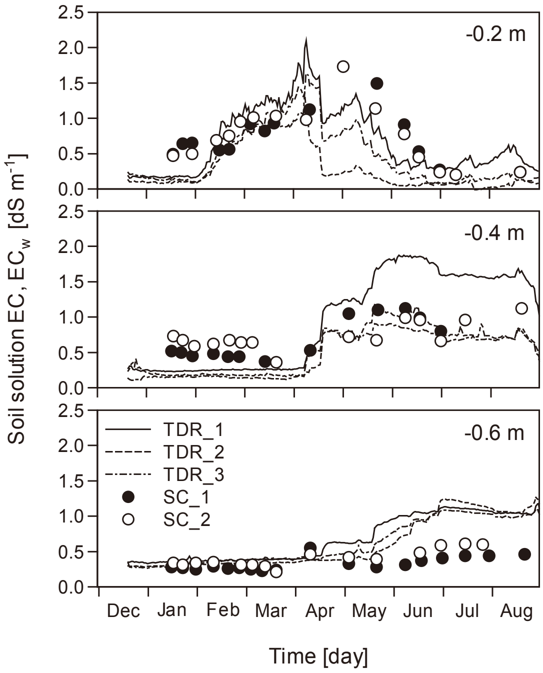

Fig. 3. Electrical conductivity of the soil solution (EC_w) at 25 °C calculated from TDR measurements compared with values obtained from the soil solution extracted using suction cups (SC_1 and SC_2)

TDR detected a gradual increase of EC_w at a depth of 0.6 m from mid-April to mid-May, the amounts measured using the suction cups did not correspond well with this result after mid-April. This discrepancy was considered attributable to the fact that more rain fell after mid-April (Fig. 2), and excessive percolation through the backfilled hole of the suction cups would have probably diluted the soil solution, thereby delivering a lower value of EC_w when using the suction cups compared with that estimated using TDR after mid-April.

4. Monitoring field nitrate concentrations

In Fig. 4, the scattered plots show the potential of using EC_w combined with site-specific regression to predict soil nitrate-nitrogen (NO_3-N) concentrations, and the results correlate relatively well to changes in EC_w. Although this regression resembles the regressions reported in previous works (Nissen et al. 1998, De Neve et al. 2000, Noborio 2005), the regression gradient is slightly lower than the regression gradients reported by these previous studies, which is considered attributable to the presence of various ions in the soil solution. Fig. 5 shows results predicting soil NO_3-N concentrations using the TDR measurements, where reasonable agreement can be observed between NO_3-N concentrations using both TDR and the solution samplers. These results suggest that the TDR measurements and the Rhoades model can provide useful tools for the continuous monitoring of soil NO_3-N concentrations in Andisol fields under transient conditions.

Conclusion

Andisols differ from other soils in their dielectric properties, thereby affecting the estimation of EC using TDR. In this study, we investigated the EC_w-EC_a-θ relationship for an Andisol and assessed the use of three models in describing these relationships. Using a soil specific ε_a-θ relationship, the simple Rhoades model proved adequately accurate in describing the EC_w-EC_a-θ relationship, while the Hilhorst model showed reasonable agreement with the experimental data. In the field experiment, EC_w values estimated using TDR with the Rhoades model showed reasonable agreement with those obtained from solution samplers. In addition, a linear regression between EC_w and NO_3-N concentrations was obtained from the field experimental data. Using a combination of this regression with the EC_w estimated from the TDR measurements and the Rhoades model is considered to provide a useful tool for monitoring soil NO_3-N concentrations in Andisol fields under transient conditions.

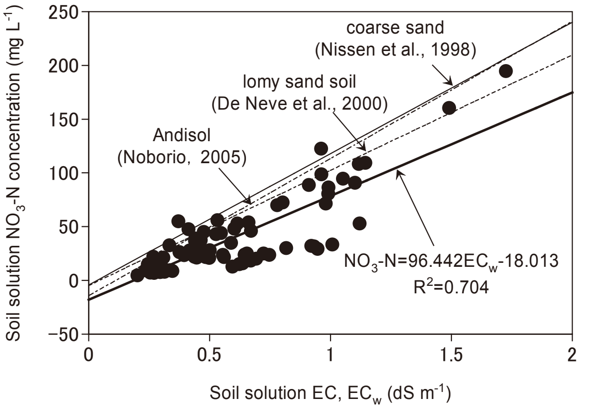

Fig. 4. Scattered plot of soil nitrate-nitrogen (NO_3-N) concentrations as a function of soil solution electrical conductivity. Linear regressions obtained in previous studies are also shown

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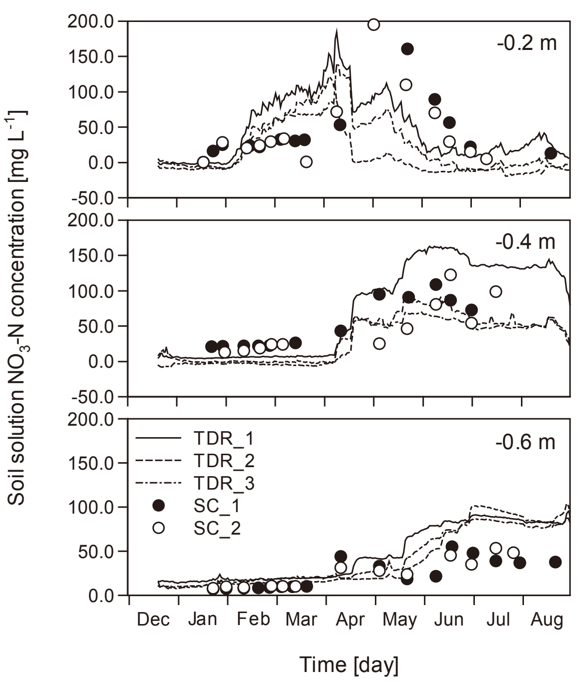

Fig. 5. Nitrate-nitrogen (NO_3-N) concentrations estimated from the TDR measurements compared with values obtained from soil solution extracted using suction cups (SC_1 and SC_2)

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