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Comparing apparent electrical conductivity measurements on a paddy field under flooded and drained conditions

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Abstract Every growing season, paddy fields are kept both flooded and drained for a significant period of time. As a consequence, these soils develop distinct physico-chemical characteristics. For practical reasons, these soils are mostly sampled under dry conditions, but the question arises how representative the results are for the wet growing conditions. Therefore, the apparent electrical conductivity (EC_a) of a 1.4 ha alluvial paddy field located in the Brahmaputra floodplain of Bangladesh was measured in both dry and wet conditions by a sensing system using the electromagnetic induction sensor EM38, which does not require physical contact with the soil, and compared both surveys. Due to the smooth water surface under wet conditions which ensured increased stability of the sensing platform, the results of the survey showed considerably reduced micro-scale variability of EC_a. Furthermore, the wet survey results more reliably furnished soil-related information mainly due to the absence of soil moisture dynamics. The differences between EC_a under wet and dry conditions were attributed to differences in soil texture, mainly the sand content variation having considerable effect on soil moisture differences when flooded following drainage. Accordingly, the largest differences between EC_a under wet and dry conditions were found in those parts of the field with a large sand content. Hence, the conclusion was that an EC_a survey on flooded fields has an added value to precision soil management.

Keywords Paddy field · Electromagnetic induction sensor · EM38 · Within-field spatial variation

Introduction

Wetland paddy cultivation in floodplain ecosystems is one of the major agricultural land use systems in all rice growing countries. In Bangladesh, floodplain alluvial soils occupy

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nearly 80% of the land area (Brammer 1981). Every growing season, paddy fields are flooded to a water height ranging between 0.10 and 0.25 m during land preparation and early crop development, respectively. This water is deliberately reduced by draining the fields during crop maturity and harvesting. The fields are under water for approximately 8 months a year. Due to the sequence of flooding and draining, the physico-chemical behavior of these soils is different than under constant aerated soil conditions (IRRI 1987). For practical reasons, these soils are mostly sampled under dry conditions. How representative the results are when applied to wet growing conditions is questionable. Therefore, the extent of obtaining high resolution soil information under both wet and dry conditions that can serve as a basis to guide precision paddy soil management was investigated.

Management of soil resources with the aid of proximal soil sensing has already been introduced for precision agriculture (Sudduth et al. 1997). Among the sensing techniques, the ones based on electromagnetic induction (EMI) are the most common (Simpson et al. 2009). Measured output of an EMI sensor translated in terms of apparent electrical conductivity (EC_a) can be interpreted to explain the within-field variability of soil properties (Rhoades et al. 1999; Saey et al. 2009). However, effects of dynamic soil moisture behavior can obscure the actual source of variation in the measured EC_a (Brevik et al. 2006). Therefore, Triantafilis et al. (2000) suggested conducting an EC_a survey when the field moisture content is about the field capacity level. Still, this strategy is difficult to apply in practice because of the spatial heterogeneity of moisture content across a field related to soil texture variation, micro-topography, fluctuating ground water levels, etc.

Because paddy fields are water saturated during the largest part of the year, it is possible to measure EC_a without the masking effect of moisture dynamics. For this purpose, a proximal soil sensing system able to operate on flooded fields as well as on dry fields was developed. It is worth mentioning that only non-invasive and non-contact proximal soil sensors are suitable for this purpose. Invasive soil sensors would fail to obtain acceptable results under flooded conditions and remote sensors would be incapable of acquiring information of the soil beneath the standing water.

The main objectives of this study were to (1) characterize the within-field spatial variability of a paddy field under flooded and drained conditions, (2) compare the results of both surveys, and (3) interpret the differences in terms of stable soil properties like texture.

Materials and methods

Study site

The study was conducted on a paddy field of the Bangladesh Agricultural University in Mymensingh. The 1.4 ha field is located in the floodplain of the river Brahmaputra (central co-ordinates 24.718708°N and 90.429306°E). It was developed on alluvial deposits and mainly consists of fine sand to silt with a clay content of approximately 15% (Brammer 1996). Paddy rice fields of the Brahmaputra floodplain are not saline and the field of investigation has a continuous paddy cultivation history of more than 35 years. Crop symptom and yield information from the same field also confirms the non-saline growing condition due to the fact that rice varieties recommended for the field are sensitive to soil salinity. An intensive paddy cultivation practice in the field usually results in three paddy harvests each year.

The floating soil sensing system (FloSSy)

To acquire high resolution soil data on both drained and flooded fields, a mobile soil sensing system: the FloSSy was developed (Islam and Van Meirvenne 2011). The EM38 (Geonics Limited, Canada) as proximal EMI soil sensor was selected primarily because of its non-invasive working principle, light weight (about 3.5 kg) and small physical dimension (1.05 m by 0.16 m by 0.05 m). More technical details and operating principles of the EMI technique and the EM38 sensor can be found in e.g. McNeill (1980) or Saey et al. (2008).

The between-coil spacing of the EM38 sensor is 1 m. Operating the sensor in the horizontal orientation, as was the case in this study, results in a depth of influence (representing 70% of its accumulated depth response under the condition of soil homogeneity) of about 0.75 m. Hence, with a water depth between 0.10 and 0.25 m, sufficient influence of the near-surface soil beneath the water layer could be measured with a floating sensor.

FloSSy consists of an EM38 put inside a waterproof housing and placed on a wooden raft (Fig. 1). A GPS receiver with differential correction (a pass to pass accuracy of ±0.20 m) was put on top of the waterproof housing so that its position represented the centre of the EM38. The wooden raft was trailed by a 12 HP vehicle (a paddy field 'power tiller'). The georeferenced sensor data were logged and processed in situ using a field laptop.

EC_a survey and data processing

The EC_a survey under dry conditions (EC_a-d), i.e. without water inundation, was conducted in July 2009 immediately after the rice harvest. In order to avoid damaging the paddy stubbles the sensor platform was raised 0.12 m from the ground during the dry survey. One month later, EC_a was measured under wet conditions (EC_a-w) just before the seasonal planting of rice seedlings, with a water height between 0.16 and 0.18 m. The traversing speed was approximately 3.6 km h^{-1}, parallel measurement lines were 1 m apart with in-line measurements every 0.25 m.

Fig. 1 FloSSy with: (*i*) laptop (protected by a plastic sheet), (*ii*) GPS antenna, (*iii*) waterproof sensor housing with an EM38 inside, (*iv*) floating platform and (*v*) power tiller

Next, the EC_a measurements were averaged to one value per m^2, they were post-corrected for instrumental drift according to the deviation from an initial diagonal measurement across the field and standardized to a reference temperature of 25°C by the method of Sheets and Hendrickx (1995):

$$ECa_{25} = ECa_{obs}\left(0.4470 + 1.4034 \cdot e^{-T/26.815}\right) \quad (1)$$

with ECa_{25} is the standardized EC_a value at 25°C and ECa_{obs} the observed EC_a value at soil temperature T (°C). During the field survey, soil temperature was recorded every hour by a bi-metal sensor pushed into the soil to a depth of 0.25 m below soil surface. The temperature remained stable at 30°C. In the following part of this paper, all EC_a measurement values refer to EC_a values at 25°C.

Variogram analysis and kriging

Information on the structure of the spatial variance of the EC_a measurements was obtained through variogram analysis. Omni-directional standardized variograms were computed for EC_a-d and EC_a-w. Both experimental variograms $\gamma(\mathbf{h})$ were best fitted with a spherical model ($\gamma(\mathbf{h}) = 0$ if $\mathbf{h} = 0$):

$$\gamma(\mathbf{h}) = \begin{cases} C_0 + C_1 \cdot \left[1.5\left(\mathbf{h}/a\right) - 0.5\left(\mathbf{h}/a\right)^3\right] & \text{if } 0 < \mathbf{h} \le a \\ C_0 + C_1 & \text{if } \mathbf{h} > a \end{cases} \quad (2)$$

with $\mathbf{h}$ the spatial lag vector, C_0 the nugget variance, C_1 the structured variance and a the range. Next, the EC_a data were interpolated to a regular grid with a resolution of 1 m by 1 m using ordinary point kriging (OK) (Goovaerts 1997). For both variogram analysis and kriging, the mapping software Surfer was used (Golden Software Inc., USA).

Soil sampling and analysis

The field was sampled twice and each time a total of 65 soil samples were collected. A random sampling scheme was used for 30 samples while the other samples were collected according to a fixed grid spacing of 7 m by 5 m to ensure an even field coverage. After both EC_a surveys, three replicated soil samples were taken within 1 m^2 at 0–0.15 m depth and pooled. Textural fraction analysis was performed for samples collected after dry survey following the sieve-pipette method while organic carbon (OC) was determined for samples collected after both surveys by the conventional Walkley and Black method. The oven-dry method was used for the moisture determination after the dry survey. During the wet EC_a survey, at each of these sampling locations, the water height was also measured using a graduated measuring scale.

Results and discussion

EC_a data

The 56 319 EC_a sensor measurements ranged from 11 to 39 mS m^{-1} for EC_a-d and from 12 to 41 mS m^{-1} for EC_a-w. Thus the mean EC_a-w (27.5 mS m^{-1}) was slightly higher than the mean EC_a-d (23.6 mS m^{-1}), which can be explained by the increased conductivity due to the water layer and saturated water–soil interface. A standard deviation of 4.4 mS m^{-1} for EC_a-d and 3.6 mS m^{-1} for EC_a-w indicated an overall higher variability within the EC_a-d data. This difference indicated spatially variable moisture dynamics within the field under drained conditions, whereas the moisture content can be considered to have a minimal and fairly homogeneous influence under flooded conditions.

Variogram analysis and kriging

Figure 2 shows the standardized experimental variograms and their spherical variogram models for EC_a-d and EC_a-w. As can be seen in Table 1, both variograms had the same range and a very similar behaviour of their structured part. However, the nugget variance was considerably higher for EC_a-d (16%) than for EC_a-w (6%). Since the measurements were conducted by the same instrument and operator, this difference was mainly related to differences in the measurement conditions. Under dry conditions, the sensor platform was pulled over the soil surface, so the uneven micro-topography created more micro-scale variability in the measurements than the smooth water surface under flooded conditions. Besides this, the homogeneous EC_a of the standing water layer in the wet condition might also have played a role in reducing the nugget variance.

Maps of EC_a-d and EC_a-w obtained by OK showed similar patterns (Fig. 3). The highest EC_a values were found in the north of the field while the lowest were measured in the south and south-east of the field. To assess the spatial distribution of this shift, $EC_a\text{-}\Delta = EC_a\text{-w} - EC_a\text{-d}$ of 5 209 wet and dry paired measurements co-located within a radius of 0.25 m was calculated which were uniformly distributed over the field. The resulting points were interpolated with OK (Fig. 4). The EC_a-Δ map shows that the shift of EC_a between wet and dry conditions was not homogeneous over the field. The largest EC_a-Δ values were found in those parts where EC_a-d and EC_a-w were the lowest. These EC_a-Δ

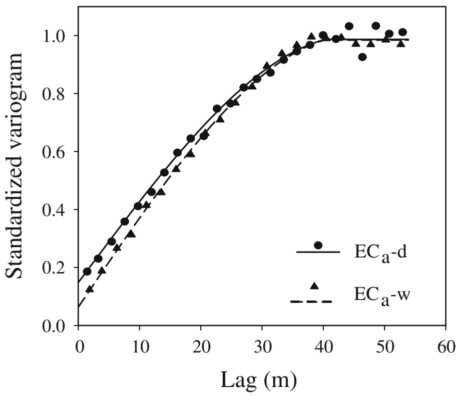

Fig. 2 The standardized experimental variograms and their spherical variogram models (*curves*) for EC_a-w (*dots*) and EC_a-d (*triangles*)

Table 1 Parameters of the standardized spherical variogram models for EC_a-w and EC_a-d

Variable	C_0	C_1	a (m)
EC_a-d	0.16	0.83	41
EC_a-w	0.06	0.93	41

C_0 the nugget variance, C_1 the structured variance and a the range

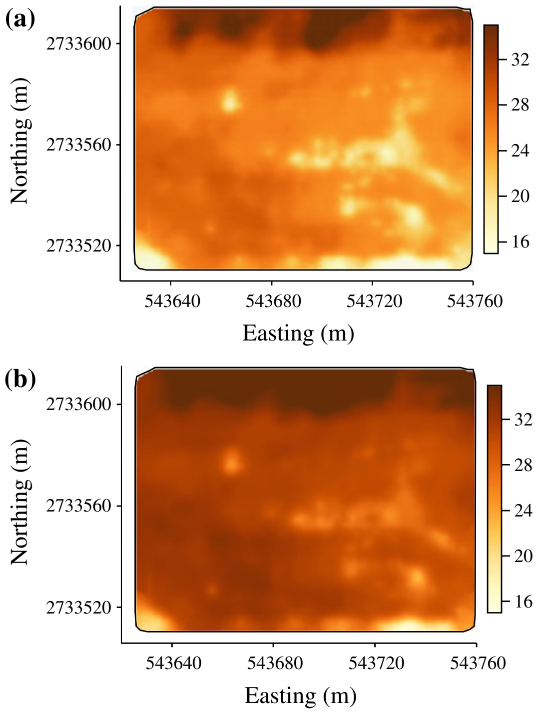

Fig. 3 Interpolated EC_a-d (**a**) and EC_a-w (**b**) measurements (mS m^{-1}). The co-ordinates conform to the Bangladesh Transverse Mercator projection with map datum Gulshan 303

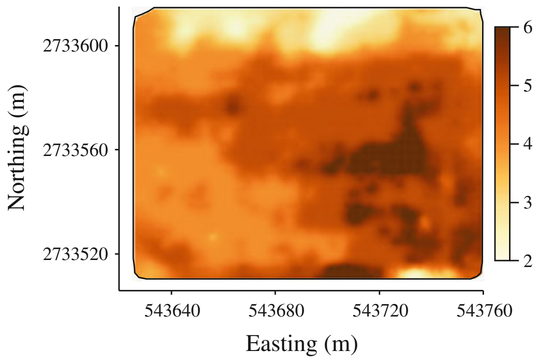

Fig. 4 Interpolated EC_a-Δ values (mS m^{-1}). The co-ordinates conform to the Bangladesh Transverse Mercator projection with map datum Gulshan 303

differences must not have been caused by the difference in the height of the sensor above the ground for the two surveys as this was within a few centimeters only.

Relation between EC_a and soil properties

Summary statistics of measured soil properties across the 65 sampling locations are presented in Table 2. According to the USDA soil texture classification the average soil texture of the field is sandy loam (average sand, silt and clay contents are 54.5, 39.6 and 5.9%, respectively). However, large variation in the coarse textural fractions (a standard deviation of 4.7% for the sand data) indicated the non-homogeneous condition of the field.

Table 2 Population parameters of EC_a, soil textural fractions and other measured soil properties; OC-d and OC-w are the organic carbon in dry and wet field conditions, respectively and OC-Δ as the numerical difference, s^2 is the variance; number of samples $(n) = 65$

Variable	Minimum	Maximum	Mean	s^2
Sand (%)	43	66	54.5	22.2
Silt (%)	30	51	39.6	20.7
Clay (%)	3	9	5.9	1.2
Volumetric moisture (%)	24.9	31.9	28.7	2.2
Water height (m)	0.16	0.18	0.17	0.0
OC-d (g kg^{-1})	0.8	1.6	1.2	0.1
OC-w (g kg^{-1})	1.2	2.0	1.7	0.3

Consequently, moisture content measured under dry conditions was variable. The average OC content was higher (1.7 g kg^{-1}) in wet condition than that of dry condition (1.2 g kg^{-1}) because of the incorporated paddy stubbles. Small difference in water height (between 0.15 and 0.17 m) under flooded condition indicated a rather limited difference in surface elevation within this field.

Next to soil moisture, it is well documented that soil texture (especially the clay fraction) is a key soil property influencing EC_a measurements under non-saline conditions (Rhoades et al. 1999; Saey et al. 2009). Although soil texture can be considered as a stable property which obviously will not have changed between the two surveys, the spatial distribution of EC_a-Δ can still be explained by soil texture. Figure 5 shows the relation between sand and EC_a-Δ at the 65 locations where soil samples were taken.

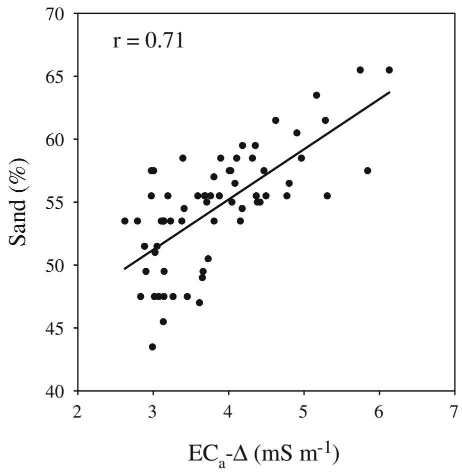

Fig. 5 Relationship between EC_a-Δ (mS m^{-1}) and sand fraction (%) at 65 locations

Table 3 Pearson correlation coefficient (*r*) between EC_a-d, EC_a-w, EC_a-Δ and relevant soil properties $(n = 65)$

Variable	Clay	Silt	Sand	Volumetric moisture	Water height	OC-w	OC-d	OC-Δ
EC_a-d	0.42	0.58	−0.64	0.37	–	–	0.26	–
EC_a-w	0.46	0.62	−0.69	–	0.34	0.36	–	–
EC_a-Δ	−0.53	−0.63	0.71	–	–	–	–	0.49

The Pearson correlation coefficient (*r*) between EC_a-d, EC_a-w, EC_a-Δ and the measured soil properties are shown in Table 3. The correlation coefficients between EC_a and soil texture were stronger than between EC_a and other soil properties. EC_a-w and soil texture had better correlation coefficients than those with EC_a-d which can be explained by the increased moisture differences due to increased coarseness of the textural fractions. This finding strongly points to a relationship between soil texture, i.e. mainly the sand content variation, and the soil moisture dynamics. The depth of the water layer above the ground for the wet survey was not a major cause driving the changes noticed in the EC_a-Δ map because the water height difference across the field was approximately 0.02 m only.

Conclusions

Although the patterns in the EC_a maps obtained by measuring a paddy field under both drained and flooded conditions did not differ very much, measuring a paddy field under flooded conditions offers several advantages. First, the nugget variance is considerably lower (10% in the test case). Furthermore, because variation in moisture content can be considered as negligible under flooded conditions, the soil EC_a response can be attributed more directly to variations in soil texture. Consequently, the relationships between soil textural fractions and EC_a are improved in flooded soil conditions.

Measuring EC_a under two contrasting moisture conditions provides additional information concerning the relationship between moisture dynamics and soil texture. This can support the evaluation of soil processes, such as leaching, allowing within-field management.

Finally, the accessibility of paddy fields for proximal soil sensing increases dramatically when measuring under flooded conditions becomes possible with equipment like FloSSy.

References

Brammer, H. (1981). *Reconnaissance soil survey of Dhaka district. Revised edition* (pp. 6–19). Dhaka: Soil Resources Development Institute.

Brammer, H. (1996). *The geography of the soils of Bangladesh* (p. 25). Dhaka: The University Press Limited.

Brevik, E. C., Fenton, T. E., & Lazari, A. (2006). Soil electrical conductivity as a function of soil water content and implications for soil mapping. *Precision Agriculture, 7*, 393–404.

Goovaerts, P. (1997). *Geostatistics for natural resources evaluation*. New York, NY: Oxford University Press.

IRRI. (1987). *Physical measurements in flooded rice soils: The Japanese methodologies*. Los Baños, Manila: International Rice Research Institute.

Islam, M. M., & Van Meirvenne, M. (2011). FloSSy: A floating sensing system to evaluate soil variability of flooded paddy fields. In J. V. Stafford (Ed.), *Proceedings of the 8th European conference on precision agriculture* (pp. 60–66). Prague, Czech Republic: University of Life Sciences.

McNeill, J. D. (1980). *Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6*. Missisauga, ON: Geonics Limited.

Rhoades, J. D., Chanduvi, F., & Lesch, S. M. (1999). *Soil salinity assessment*: *Methods and interpretation of electrical conductivity measurements*. FAO Rep. 57. Rome: FAO.

Saey, T., Simpson, D., Vermeersch, H., Cockx, L., & Van Meirvenne, M. (2008). Comparing the EM38DD and DUALEM-21S sensors for depth-to-clay mapping. *Soil Science Society of America Journal, 73*, 7–12.

Saey, T., Van Meirvenne, M., Vermeersch, H., Ameloot, N., & Cockx, L. (2009). A pedotransfer function to evaluate the soil profile textural heterogeneity using proximally sensed apparent electrical conductivity. *Geoderma, 150*(3–4), 389–395.

Sheets, K. R., & Hendrickx, J. M. H. (1995). Non-invasive soil water content measurement using electromagnetic induction. *Water Resource Research, 31*, 2401–2409.

Simpson, D., Lehouck, A., Verdonck, L., Vermeersch, H., Van Meirvenne, M., Bourgeois, J., et al. (2009). Comparison between electromagnetic induction and fluxgate gradiometer measurements on the buried remains of a 17th century castle. *Journal of Applied Geophysics, 68*(2), 294–300.

Sudduth, K. A., Hummel, J. W., & Birrell, S. J. (1997). Sensors for site-specific management. In F. J. Pierce & E. J. Sadler (Eds.), *The state of site-specific management for agriculture* (pp. 183–210). Madison, WI: ASA-CSSA-SSSA.

Triantafilis, J., Laslett, G. M., & McBratney, A. B. (2000). Calibrating an electromagnetic induction instrument to measure salinity in soil under irrigated cotton. *Soil Science Society of America Journal, 64*, 1008–1017.