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## Effects of agronomic practices on the physico-chemical properties of soil waters in rice culture

Muhammad Farrakh NAWAZ<sup>1,2,\*</sup>, Guilhem BOURRIE<sup>3,4</sup>, Fabienne TROLARD<sup>3,4</sup>, Jean-Claude MOURET<sup>5</sup>, Pierre HENRY<sup>6</sup>

<sup>1</sup>INRA, UR 1119, Géochimie des Sols et des Eaux, Aix-en-Provence, France

<sup>2</sup>Department of Forestry, University of Agriculture Faisalabad, Pakistan

<sup>3</sup>INRA, UMR 1114 Emmah, F\_84911 Avignon, France

<sup>4</sup>UAPV, UMR 1114 Emmah, F\_84911 Avignon, France

<sup>5</sup>INRA, UMR Innovation, Montpellier, France

<sup>6</sup>College de France, 13545 Aix en Provence cedex 04, France

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**Abstract:** Lowland rice cultivation under hydromorphic conditions is a very dynamic system due to continuous rhizospheric interactions and these interactions are largely influenced by anthropic interventions. Understanding of continuous biogeochemical changes and the effects of environmentally friendly residue management practices on this system is crucial for the sustainability of rice culture. Two rice-cultivated plots with different residue management practices—one with buried residues and the other with burnt residues—were studied by in situ monitoring of the soil solution to understand the quick changes in the dynamic medium of rice culture. In this study, 2 multiparametric probes, each consisting of measurement cells and internal memory, were used to determine automatically pH, Eh, temperature, and electrical conductivity (EC) of soil solution every hour throughout the entire rice growing period. The results showed that biogeochemical reactions are largely influenced by irrigation and fertilization practices. Incorporation of rice residues resulted in more reductive conditions and higher temperatures as compared to burning of rice residues. Fourier and covariance analyses showed that there existed a period of 24 h for EC, pH, and temperature while there was no period for redox potentials, which suggested the existence of daily variations in rice culture possibly related to solar cycles.

**Key words:** Fourier analysis, covariance, multiparametric probe, redox conditions, rice residues

### 1. Introduction

Choice of crop residue management practices and the understanding of its impacts on soil and environment are increasing in importance with the current renewed focus on agricultural sustainability. Burning of rice straw is the traditional method of crop residue disposal in many countries. This practice is supposed to have advantages for disease and pest control, and labor and energy savings. However, open burning of crop residues contributes to emissions of carbon dioxide, carbon monoxide, methane, nitrogen oxides, sulfur dioxide, and harmful air pollutants such as polycyclic hydrocarbons and dioxins that can cause serious health hazards (Gadde et al. 2009). Therefore, such a harmful practice is banned in Europe and California and alternative methods are recommended (Eagle et al. 2000).

Incorporation of crop residues in soil has been reported to be advantageous over burning and physical removal from the viewpoint of nutrient cycling and soil fertility (Zeleeke et al. 2004). Crop residues favorably influence

the biological, chemical, and physical properties of the soil. They increase the soil microbial biomass, nitrogen mineralization, organic carbon, and total N levels in the soil (Bierke et al. 2008). However, in lowland paddy fields, incorporation of rice straw can result in more reducing conditions than in paddy fields where rice straw is removed (Gao et al. 2002). These severe reducing conditions can induce abiotic N immobilization by soil organic matter due to the binding of proteinous compounds to the lignin-derived phenolic components (Bierke et al. 2008) and plant toxicity due to sulfide accumulation (Gao et al. 2004). Furthermore, reducing conditions induced by straw incorporation can influence germination. Thus, monitoring the changes in the biogeochemical properties of soils under different postharvest management practices is crucial for better management of paddy soils.

In general, oxido-reduction processes in submerged soils are explained by many authors (Takai and Kamura 1966; Ponnampurna 1972; Flessa and Fischer 1992)

\* Correspondence: [kf\\_uaf@yahoo.com](mailto:kf_uaf@yahoo.com)

but most of the studies are independent of the culture or the postharvest management practices. Gao et al. (2004) carried out experiments to examine the effect of the incorporation of rice straw on the redox status of paddy soils in laboratory conditions but no concise information was presented on other physico-chemical parameters of the soil solution (pH, electrical conductivity (EC), or temperature). Furthermore, these studies were not continuous; rather they consisted of 1 or 2 readings per week. Therefore, several previous studies suggested the need for long-term continuous study of soil solutions in paddy fields to understand the short-term changes during cultivation (Couchat et al. 1993). The aim of the multiparametric probe used by Cary and Trolard (2006) in paddy fields in Camargue was to understand the mobility of elements and geochemical processes in the paddy fields under alternative aerobic and anaerobic conditions without any postharvest management practices and it was not focused on the superficial layers of the rice system.

The objectives of our study were to monitor the biogeochemical changes in soil solutions in 2 plots with different agronomic postharvest practices during the entire rice cultivation period by measuring the electro-chemical (EC, pH and pe) and electro-physical (t°C) parameters of soil solution, to investigate the influence of the day and night cycles on these parameters of the soil solution in the bulk soil at rooting depth, and to understand the influence of agricultural practices such as irrigation and urea application on the reducing conditions throughout the rice cultivation period.

## 2. Materials and methods

### 2.1. Experimental site

The study was conducted in the Camargue (Rhône delta) under a Mediterranean climate in 2 neighboring plots located at 31°62'E and 48°29'N. In plot R-178 rice residues are burnt, while in plot R-179 the rice residues are incorporated in soil for 20 years. The altitudes for R-178 and R-179 were 0.61 m and 0.24 m, respectively. In general, the soils of both plots are alluvial, clay loam (about 40% clay, 56% silt, and 4% sand), saline (EC can be up to 6 mS cm<sup>-1</sup>), with hydromorphic conditions and were deposited in the Holocene by the River Rhône. These soils are anthropogenically transformed soils since they have continuously been under rice culture for about 50 years. Ten soil samples at random were collected at a depth of 5–10 cm from each plot and then they were mixed to prepare 3 samples for the determination of physico-chemical properties of soil in the rhizosphere (Table). The Table shows more Na<sup>+</sup> and larger EC values in the plot R-179 than in R-178, and so R-179 was more saline compared to R-178.

In April 2009, water as well as herbicide was applied between 25 April and 5 May to control the weeds in both plots. Pre-germinated seeds were sown on 7 May in both plots at the rate of 220 kg ha<sup>-1</sup>. Water drainage for rooting was carried out 15 days later in both plots but water was applied again 3 days after in R-179 and 7 days after in R-178; irrigation was applied as early as possible in R-179 to ensure that salinity did not appear at the soil surface (as plot R-179 was more saline than R-178) but in R-178

**Table.** Some soil properties of the 2 paddy plots in the study area.

	R-178 (residues burnt)	R-179 (residues incorporated)
<b>Organic matter (%)</b>	2.20 ± 0.2	2.29 ± 0.46
<b>C/N ratio</b>	8.76 ± 0.75	8.34 ± 0.39
<b>Ca (me 100 g<sup>-1</sup>)</b>	42.48 ± 0.42	41.02 ± 0.41
<b>Mg (me 100 g<sup>-1</sup>)</b>	2.68 ± 0.13	4.52 ± 0.57
<b>K (me 100 g<sup>-1</sup>)</b>	0.43 ± 0.02	0.56 ± 0.08
<b>Na (me 100 g<sup>-1</sup>)</b>	0.39 ± 0.05	1.71 ± 0.70
<b>*EC (mS cm<sup>-1</sup>)</b>	315.6 ± 27	787.3 ± 120.1
<b>pH</b>	8.18 ± 0.03	8.14 ± 0.01
<b>**CEC (me 100 g<sup>-1</sup>)</b>	11.02 ± 0.17	10.11 ± 0.76

\*EC stands for electrical conductivity.

\*\*CEC stands for cation exchange capacity.

irrigation was carried out at the normal time. The plots were fertilized (urea at 250 kg ha<sup>-1</sup>) in mid-June.

### 2.2. Use of multiparametric probes

We used 2 multiparametric probes, type IDROPROBE of DERLIN with external diameter of 7.5 cm and total length of 45 cm, manufactured by IDROMAR, developed mainly for water quality monitoring in both marine coastal areas and inland waters (lagoons, lakes, rivers, and reservoirs) (Figure 1). Each multiparametric probe was equipped with a combined pH electrode, a combined platinum electrode of oxido-reduction and a reference electrode of Ag/AgCl, a sensor for electrical conductivity, a sensor for temperature, and a stirrer for homogenizing the solution in the measurement cell. The oxido-reduction potentials were converted to the normal hydrogen scale (NHE) with temperature correction (Nawaz 2010).

All the sensors were verified and calibrated in the laboratory before and after the installation of the probes following the procedure described by Nawaz and Bourrié (2012). One multiparametric probe per plot was installed

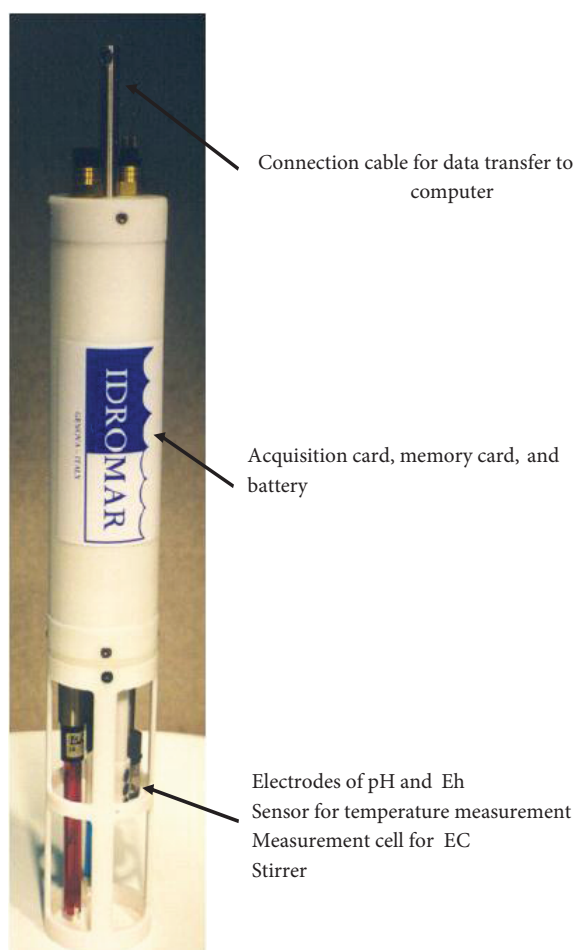
1 day before sowing (6 May 2009) at 5–10 cm in both rice plots. The measurements were taken 1 day after the installation of the probes in order to achieve equilibrium between the probes and soil solution. There was a couple of hours' weekly interruption in the data collection due to the need to recharge the battery because of low battery life. This problem was overcome by replacing the battery for one with larger capacity. The probes remained in the rice plots until 03/09/2009 (3 weeks before the harvesting) as flooding of paddy fields was stopped. Measurements of all the parameters (pH, redox potential, temperature, and EC) were carried out every hour during the entire rice cultivation period. Ten repeated measurements per parameter were taken but only the average of them was recorded in the internal memory. Measurement time between any subsequent parameters was 10 s and the stirrer started working 1 min before the measurement time.

### 2.3. Signal treatment and statistical analysis

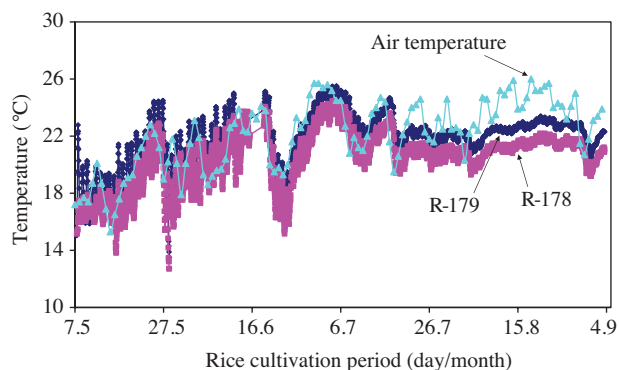
Fourier analysis and cross-covariance analysis are useful tools to observe the existence of a period in the data and to see, if it exists, a correlation among recorded parameters. These types of analysis are frequently used in physics, geodynamics, and climatology but are rarely used in agronomic or geochemical studies. Fourier analysis was carried out in Excel while cross-covariance analysis was carried out using the software MATLAB. Fourier analysis describes the structure of data by indicating the presence of any periodicity in the long-term recorded signals and helps us to present the data in the form of a periodogram. Cross-covariance analysis gives us information about correlations between the data structures of 2 parameters and shows whether these 2 parameters are in the same phase.

### 3. Results

It can be seen in Figure 2 that until mid-July soil solution temperatures (SSTs) in both plots (R-178 and R-179) followed the variations in air temperatures; then the SSTs were lower than the daily average of air temperatures



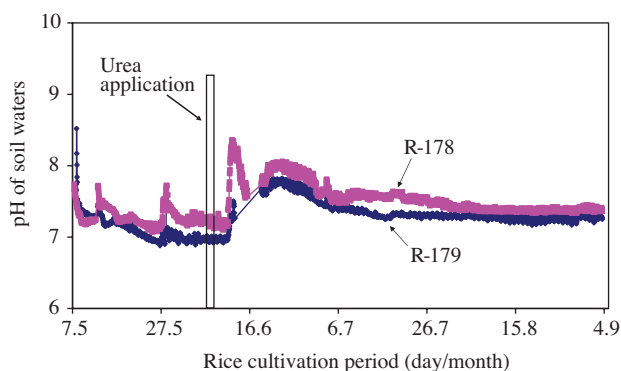
**Figure 1.** Description of different compartments of the multiparametric probe.



**Figure 2.** Comparison of air temperatures and soil solution temperatures (SSTs) of 2 plots under different rice residue management practices (R-178 and R-179).

for the rest of the study period. Larger variations in SST were observed during the early rice cultivation period (May–June) than during the late cultivation period (July–August), when curves are relatively smooth. The SST of R-179 (incorporation of rice residues) remained, on average, 1.3 °C higher than that of R-178 (burnt rice residues) during the entire cultivation period.

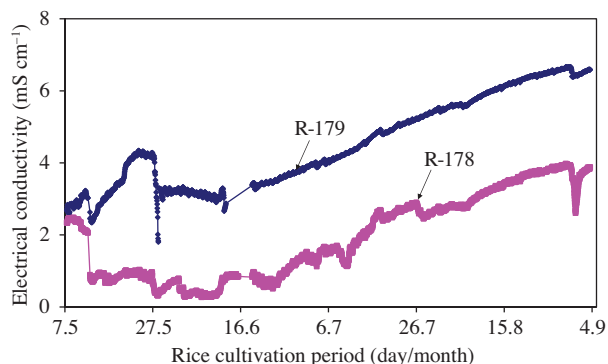
The pH of soil solutions in both plots (R-178 and R-179) varied between 6.9 and 8.4 and the variations in pH were mostly due to either water application (mid-May and 27 May) or urea application (1 June) as shown in Figure 3. In both plots (R-178 and R-179), initial flooding resulted in a decrease in pH; afterwards, in both plots, the pH remained at equilibrium near 7 except in mid-May and on 27 May due to water application, which resulted in a slight increase in pH. In early June, urea and fresh water application had an accumulative effect and caused a sudden increase in the pH of both plots, which took more time to stabilize at equilibrium values (again near 7) in R-178 than in R-179.



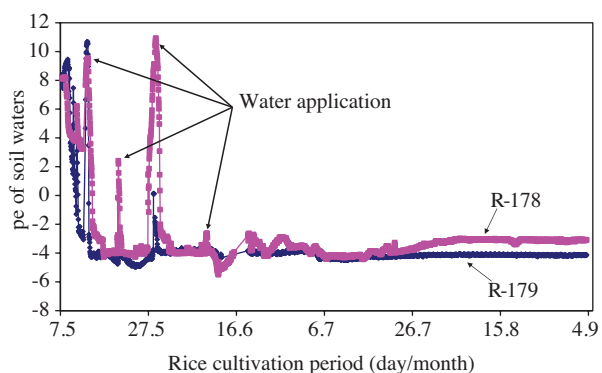
**Figure 3.** The pH values of soil solutions for 2 rice cultivated plots with different rice residue management practices (R-178 and R-179).

It can be observed from Figure 4 that the electrical conductivity (EC) of R-179 was higher (2.5–6.7 mS cm<sup>-1</sup>) than that of R-178 (2.5–4 mS cm<sup>-1</sup>). Each irrigation practice (mid-May and 27 May) decreased the EC by diluting the soil solutions during the rice cultivation period. An increase was observed after the last irrigation due to urea fertilizer application (1 June) in both plots (R-179 and R-178).

Just after the arrival of fresh water during the first water application, a sudden increase in redox potentials in both plots (irrespective of postharvest practice) was noted just after the flooding (Figure 5). Just 3 days after the flooding, reductive conditions were observed in R-179. In contrast, more time was needed before the depletion of oxygen and establishment of the reductive conditions in R-178. Once oxygen was completely depleted, the redox potentials were stabilized at pe value about -4 in both plots. The peaks



**Figure 4.** Electrical conductivity (EC) of soil solutions of 2 plots with different rice residue management practices (R-178 and R-179).

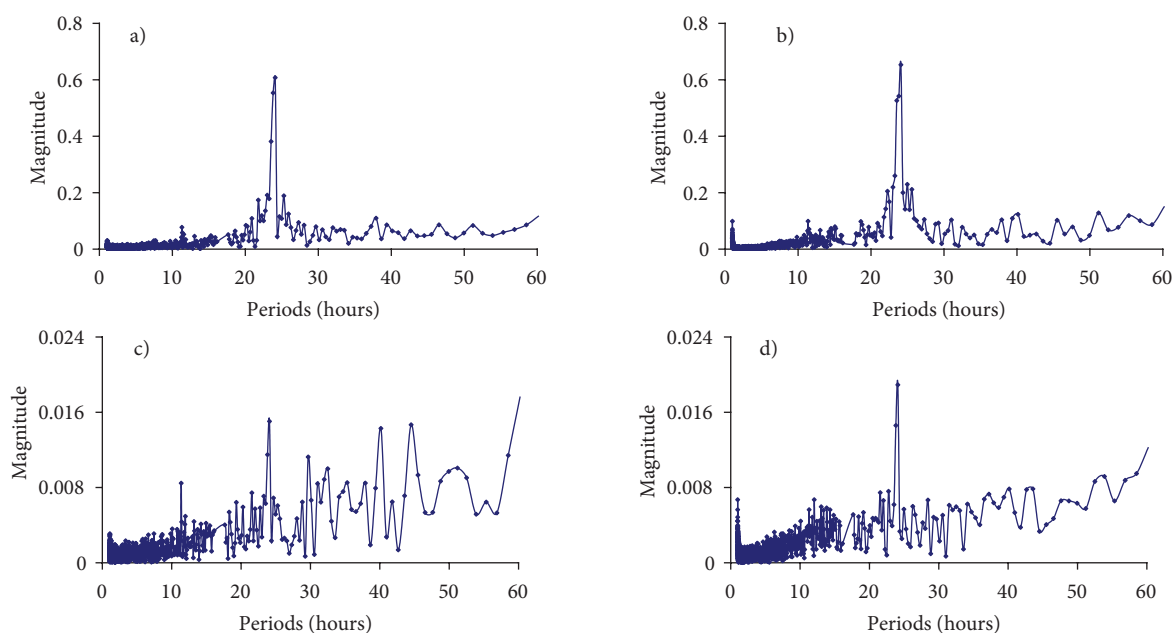


**Figure 5.** Redox potentials (pe) of soil solutions of 2 plots with different rice residue management practices (R-178 and R-179).

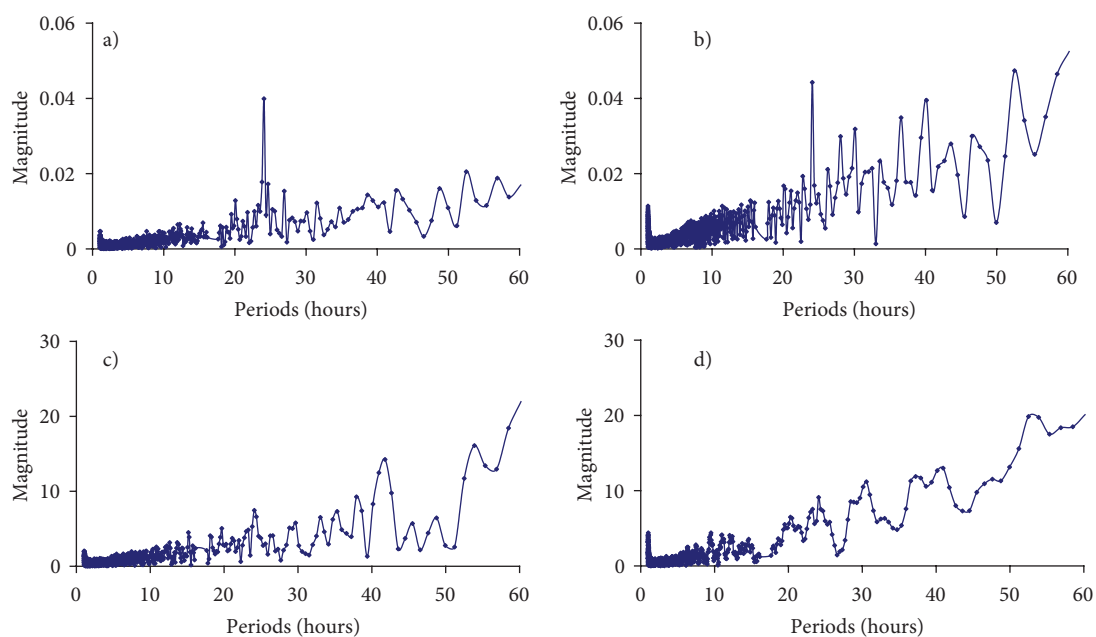
observed (spontaneous rise and fall of redox potential) on 12 May, 20 May, 28 May, and mid-June. After mid-June, redox potentials were stable at pe values highly reductive (about -4) such that R-179 > R-178.

The results obtained after Fourier analysis are presented in the form of a periodogram for temperature, pH, EC, and Eh for R-178 and R-179 in Figures 6 and 7. In all of the periodograms, the Y-axis represents the magnitude and the X-axis represents the periods (in hours per cycle). Furthermore, sharpness of the peak determines the reliability of that period. Both temperature and EC in the plots showed a period of 24 h. For pH, a peak is also present at the period of 24 h in both plots but this peak is more considerable in R-179 than it is in R-178. For redox potential, a peak is also present at the 24-h period in both plots but this peak is not sharp and there are many other peaks in different periods. The larger period resulted in worse significance or a higher P value because of a smaller number of data points.

Covariance analysis allows us to correlate 2 variables and it shows their phases and correlation. If they are in the same phase, 2 cases can be observed: either



**Figure 6.** Fourier analysis (FA) for temperature and pH for both plots. a) FA for temperatures in R-178; b) FA for temperature in R-179; c) FA for pH in R-178; d) FA for pH in R-179.



**Figure 7.** Fourier analysis (FA) for electrical conductivity (EC) and redox potentials (Eh). a) FA for EC in R-178; b) FA for EC in R-179; c) FA for Eh in R-178; d) FA for Eh in R-179.

both variables show simultaneous maximum or the maximum of the first variable is observed as the other parameter is at its minimum. If they are in different phases, the maximum of the first variable regularly

occurs before or after the maximum or the minimum of the second variable. Here, in the presented graphs (Figure 8), the Y-axis represents the magnitude and the X-axis represents the hours.

The graphs (in Figure 8) show that there is no highly significant correlation between any 2 parameters, but only covariance for temperature/pH and temperature/EC had regular oscillations as compared to the others. In the case of covariance between temperature and pH, the first downward peak was present at  $t = 0$ ; then the subsequent downward peaks appeared in the 24-h interval. The reverse was observed for covariance between temperature and EC: an upward peak was observed after every 24 h. Therefore, temperature, pH, and EC were in the same phase but temperature was positively correlated with EC and negatively correlated with pH.

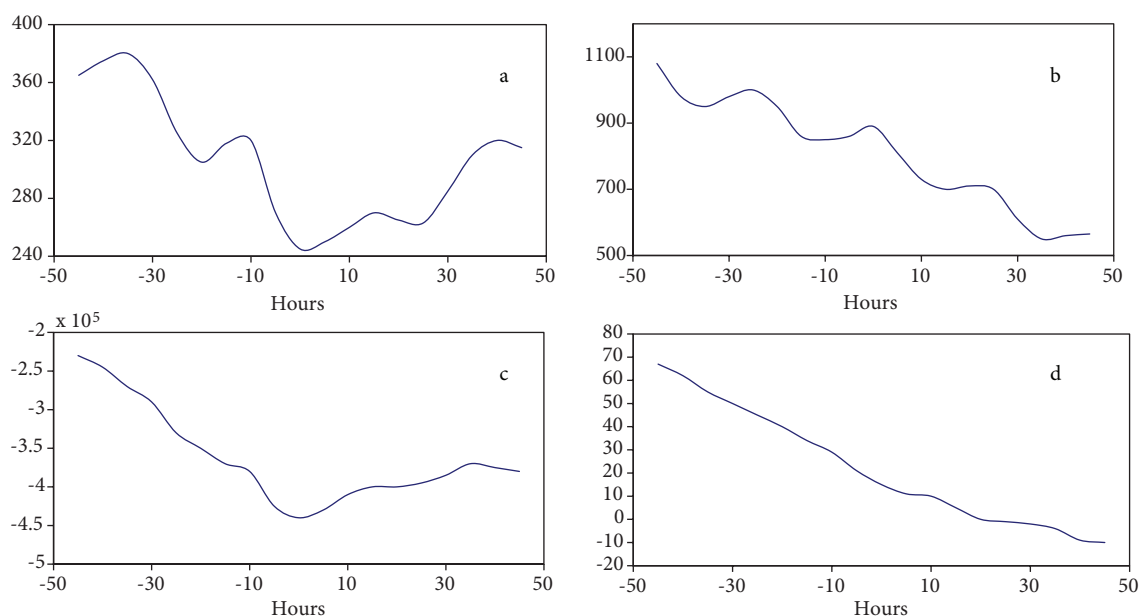
#### 4. Discussion

The reduced day–night SST variations and SST lower than air temperatures at the end of the rice cultivation period can be linked to the shadow of rice plants, which hindered the direct contact of sun rays with surface waters. The higher SST values in R-179 as compared to R-178 can be due to the difference in postharvest management practices between the plots. It is reported that incorporation of rice residues influences the composition, diversity, and population of microorganisms (Mandal et al. 2004). It increases the microbial activity, microbial biomass, and microbial respiration in the soil, which can be responsible for higher temperatures in R-179 (Devevre and Horwath 2000; Singh et al. 2007). The SST in the R-179 can also be higher due to change in radiant energy balance and insulation due to the different thickness of water in both plots (Mandal et al. 2004).

The higher pH of irrigation water (8.4) was responsible for the increase in pH in both plots after each irrigation practice. The applied urea can hydrolyze as much as 80% in only 5 days (Bellitürk and Saglam 2005). This hydrolysis reaction produces  $\text{HCO}_3^-$  and increases soil alkalinity as well as pH, but ammonium produced in this reaction dissociates into  $\text{NH}_3$  and  $\text{H}^+$  release from this reaction can decrease pH. Urea application caused pH increase in both plots, but transformation of ammonium to ammonia, other cations' absorption by plants that induce  $\text{H}^+$  release, calcite dissolution, and oxidation of iron minerals are responsible for regulation of pH in the soil after fertilization (Bellitürk and Saglam 2005).

Higher EC in R-179 as compared to R-178 was attributed to higher initial salinity (more  $\text{Na}^+$ ) of R-179; in fact, incorporation of rice residues may be responsible for increased EC in R-179 due to increased microbial activity and biodegradation of rice residues in R-179 as reported by Mandal et al. (2004). Furthermore, it is also reported that fertilizer application, green manuring, and low water contents can result in higher EC (Jacobs and Timmer 2005).

Early reductive conditions in the R-179 can be attributed to the postharvest management practices such as incorporation of rice straw and flooding during winter for 20 years. Eventually, these practices may affect the microbial functional diversity as reported by Bending et al. (2002). Therefore, the presence of more diverse populations of microorganisms in R-179 for decomposition of the organic matter could result in the quick utilization of



**Figure 8.** Results of covariance analysis for R-178. a) between temperature and pH; b) between temperature and EC; c) between temperature and Eh; d) between pH and EC.

oxygen and appearance of early reductive conditions. A quick decrease in the redox potentials when rice straw has been incorporated and a prolonged decrease in redox potentials when rice straw has been burnt are also reported by Gao et al. (2002). Irrigation influenced the redox potentials; however, rice incorporation-induced relatively lower redox potentials were observed in R-179.

According to Bohn et al. (1985), at pe values from 3.3 to 8.5, biological reduction of  $\text{NO}_3^-$  to  $\text{NO}_2^-$  in paddy fields occurs even in the absence of water but flooding of rice fields changes the system completely and rapidly with the beginning of reduction in  $\text{Mn}^{4+}$  and  $\text{Fe}^{3+}$  at pe values below 1.5. When the pe values are in the range of  $-3.8$  to  $-5$ , a reduction in  $\text{SO}_4^{2-}$  and  $\text{CH}_2\text{O}$  occurs with the production of hydrogen sulfide ( $\text{H}_2\text{S}$ ) and methane ( $\text{CH}_4$ ). As pe values in R-178 and R-179 were below  $-3.4$  after just 1 week of cultivation, during the majority of the cultivation period pollutant gases can be released. Reduction in the release of greenhouse gases and maintenance of optimum redox potentials can be achieved by managing the irrigation timings and water levels (Johnson et al. 2005; Minamikawa and Sakai 2006).

Fourier analysis confirms the presence of daily cyclic variations in physico-chemical parameters in the rhizosphere under both agricultural practices. The sources of these daily variations are biotic (microbial population and plant physiological processes; photosynthesis and nutrient absorption) and/or abiotic processes (daily solar cycles and air temperatures; and precipitation/dissolution processes). These results of covariance analysis are in accordance with Fourier analysis as a specific structure of data was observed for temperature, EC, and pH, while no specific structure of data was observed for Eh. Apart

from other processes (dissolution/precipitation, Nernst's law, etc.), evapo-transpiration processes are the major reason for this positive EC/temperature correlation, while an increase in photosynthetic activity and root absorption processes with the release of  $\text{H}^+$  can be the major cause of the negative correlation between pH and temperature.

Measurement of physico-chemical parameters (pH, Eh, temperature, and EC) in the rhizosphere throughout the rice cultivation period with multiparametric probes allowed us to understand the effect of natural, anthropic (agricultural practices), and physico-chemical interactions during rice cultivation under 2 different postharvest management practices (straw incorporation and straw burning). It is concluded that weather conditions (temperatures) played an important role in the evolution of physico-chemical parameters in rice culture, while the effects of human interventions in the form of water management operations and/or fertilizer application were significant and dominant. It was found that incorporation of rice straw resulted in more reducing conditions in soil solutions as compared to burning of rice straw. In the regions of the world where direct sowing of rice is practiced during lowland rice cultivation like in Camargue (France), higher reducing conditions due to rice straw incorporation can be harmful during the germination stage.

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### References

- Belliturk K, Saglam MT (2005) A research on the urea hydrolysis rate in the soils of Thrace region. *J Cent Eur Agric* 6: 107–114.
- Bending G, Turner M, Jones J (2002) Interactions between crop residue and soil organic matter quality and the functional diversity of soil microbial communities. *Soil Biol Biochem* 34: 1073–1082.
- Bierke A, Kaiser K, Guggenberger G (2008) Crop residue management effects on organic matter in paddy soils—The lignin component. *Geoderma* 146: 48–57.
- Bohn H, McNeal B, O'Connor G (1985) Oxidation and reduction. In: *Soil Chemistry*. John Wiley, New York.
- Cary L, Trolard F (2006) Effects of irrigation on geochemical processes in a paddy soil and in ground waters in Camargue (France). *J Geochem Explor* 88: 177–180.
- Couchat P, Bois JF, Puard M (1993) Rice responses to environmental conditions. *Agronomy* 1: 73–85.
- Devevre O, Horwath W (2000) Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. *Soil Biol Biochem* 32: 1773–1785.
- Eagle A, Bird J, Horwath W, Linquist B, Brouder S, Hill J, van-Kessel C (2000) Rice yield and nitrogen utilization efficiency under alternative straw management practices. *Agron J* 92: 1096–1103.
- Flessa H, Fischer W (1992) Plant-induced changes in the redox potentials of rice rhizospheres. *Plant Soil* 143: 55–60.
- Gadde B, Bonnet S, Menke C, Garivait S (2009) Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environ Pollut* 157: 1554–1558.
- Gao S, Tanji K, Scardaci S (2004) Impact of rice straw incorporation on soil redox status and sulfide toxicity. *Agron J* 96: 70–76.
- Gao S, Tanji K, Scardaci S, Chow A (2002) Comparison of redox indicators in a paddy soil during rice-growing season. *Soil Sci Soc Am J* 66: 805–817.



- Jacobs D, Timmer V (2005) Fertilizer-induced changes in rhizosphere electrical conductivity: relation to forest tree seedling root system growth and function. *New Forests* 30: 147–166.
- Johnson S, Alberto M, Angeles O, Buresh R (2005) Optimum redox potential in flooded paddy soil: managing rice (*Oryza sativa* L.) straw and irrigation for sustainable enhancement of productivity. *Philipp J Crop Sci* 30: 44.
- Mandal K, Misra A, Hati K, Bandyopadhyay K, Ghosh P, Mohanty M (2004) Rice residue-management options and effects on soil properties and crop productivity. *J Food Agric Environ* 2: 224–231.
- Minamikawa K, Sakai N (2006) The practical use of water management based on soil redox potential for decreasing methane emission from a paddy field in Japan. *Agr Ecosyst Environ* 116: 181–188.
- Nawaz MF (2010) Geochemistry of hydromorphic soils and waters under rice culture and forest—continuous measurements, thermodynamic modelling and kinetics. Ph.D. Thesis. Université d'Aix Marseille III. France, p. 18.
- Nawaz MF, Bourrié G (2012) Development of sensor calibration against standards using measurement software TestPoint™-CEC and application to the verification of pH electrodes. *J Chem Soc Pakistan* 34: 9–15.
- Ponnamperuma F (1972) The chemistry of submerged soils. *Adv Agron* 24: 29–96.
- Singh S, Batra R, Mishra M, Kapoor K, Goyal S (2007) Decomposition of paddy straw in soil and the effect of straw incorporation in the field on the yield of wheat. *Z. Pflanz Bodenkunde* 155: 307–311.
- Takai Y, Kamura T (1966) The mechanism of reduction in waterlogged paddy soil. *Folia Microbiol* 11: 304–313.
- Zelege T, Grevers M, Si B, Mermut A, Beyene S (2004) Effect of residue incorporation on physical properties of the surface soil in the South Central Rift Valley of Ethiopia. *Soil Till Res* 77: 35–46.