Soil Science and Plant Nutrition

ISSN: 0038-0768 (Print) 1747-0765 (Online) Journal homepage: http://www.tandfonline.com/loi/tssp20

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**To cite this article:** Lam Nguyen, Tetsuhiro Watanabe & Shinya Funakawa (2014) Spatiotemporal variability in soil salinity and its effects on rice (Oryza sativa L.) production in the north central coastal region of Vietnam, Soil Science and Plant Nutrition, 60:6, 874-885, DOI: 10.1080/00380768.2014.961030

**To link to this article:** http://dx.doi.org/10.1080/00380768.2014.961030

Published online: 01 Oct 2014.

*Soil Science and Plant Nutrition* (2014), **60**, 874–885 http://dx.doi.org/10.1080/00380768.2014.961030

ORIGINAL ARTICLE

# Spatiotemporal variability in soil salinity and its effects on rice (Oryza sativa L.) production in the north central coastal region of Vietnam

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**Abstract**

To better understand the adverse impacts of soil salinization and promote rice (Oryza sativa L.) production in crops from the north central coastal region of Vietnam, the spatiotemporal variability of soil salinity and its effects on rice production were investigated. Experiments were conducted at 19 plots widely distributed in the Quang Phuoc commune, in the Quang Dien district of the province of Thua Thien Hue in the north central coastal region of Vietnam. We determined the elevation of the 19 plots to evaluate the influence of elevation on salt accumulation. Soil samples from the 19 plots were collected in January, May and September 2012 and 2013 to study the spatiotemporal variability of salinity. A soil saturation paste was prepared and used to measure electrical conductivity (ECe). The elevation measurements obtained suggest that the research site could be divided into low- and high-elevation plots, with elevation of the low-elevation plots ranging from –0.52 to 0.07 m and the high-elevation plots from 0.26 to 0.86 m (one of the sampling plot was designated with an elevation of 0 m and the elevations of the remaining 18 plots were measured relative to that). ECe was high at low elevations. In conclusion, although the differences in elevation between the 19 plots were very small (centimeters to decimeters), they still led to large differences in soil salinity levels. In the high-elevation plots, soils were irrigated with freshwater, thus maintaining low ECe levels throughout the year (< 1.0 dS $m^{-1}$). In contrast, in the low-elevation plots, soils were subject to seawater intrusion, resulting in high ECe levels in all seasons (> 1.9 dS $m^{-1}$). We recommend several solutions to limit the unfavorable effects of salinity and promote rice production. First, a comprehensive dike system should be constructed along the lagoon to prevent seawater intrusion onto land. Second, it will be necessary to construct adequate drainage facilities in the depressed areas to promote rapid water drainage into canals during and after flooding and irrigation. Third, because ECe was high from May to September, adequate fresh irrigation water should be frequently supplied to lower the ECe during this period.

**Key words:** elevation, depression, lagoon, paddy, saturation paste.

## INTRODUCTION

At present, salinization is the second most widespread soil problem in rice (Oryza sativa L.)-growing countries (after drought) and is considered to be a serious constraint on rice production worldwide (Ghafoor *et al.* 2004). In Vietnam, in particular the north central coastal region of the country, soil salinization is considered to be one of the most serious problems affecting rice and other crops such as bean (Arachis hypogaea L.), onion (Allium fistulosum L.) and maize (Zea mays L.). Salinization is mainly due to the inundation of seawater during high tidal action and ingress through creeks (Lang *et al.* 2010). As a result of the effects of salinization, the average yield of rice and maize in the north central coastal region is low, about 0.8–1.5 tons $ha^{-1}$ and 1.0–2.0 tons $ha^{-1}$, respectively (Lang *et al.* 2010). The national average yield of rice and maize in 2010 was 5.3 and 4.1 tons $ha^{-1}$, respectively (General Statistics Office of Vietnam 2014a).

In the past, problems associated with saline soils weren't given much attention by the Vietnamese government because of the small population of the country. However,

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*Received 13 February 2014.*
*Accepted for publication 29 August 2014.*

in recent years, the rapid increase in population has created a growing demand for food and put high pressure on food security. From 2000 to 2012, the population of Vietnam increased from 77.0 to 88.8 million people, while rice cultivation areas increased just slightly from 7.7 to 7.8 million ha (General Statistics Office of Vietnam 2014b). Hence, the reclamation of saline soils and the potential for it to aid socioeconomic development in the north central coastal zones is gaining attention.

Among the provinces in the north central coastal region of Vietnam, agricultural land in the province of Thua Thien Hue is seriously affected by soil salinization. In this region, about 2500 ha of agricultural soils adjacent to the Tam Giang lagoon (the biggest lagoon in Southeast Asia, about 22,000 ha) are saline (Dan *et al.* 2006). It is therefore urgent to develop practical solutions to alleviate the adverse effects of soil salinization on agricultural production in Thua Thien Hue.

To address this need, spatial and temporal variability in soil salinity and its effects on rice production need to be investigated, because information on spatial and temporal variability in soil salinity can be used to select the appropriate site-specific methods for the amelioration of saline soils (Qadir *et al.* 2000; Zheng *et al.* 2009). Li *et al.* (2007) suggested that there is both spatial and temporal variation in soil salinity and both types of variability need to be considered to achieve the ultimate goal of sustainable cropping systems.

The important role of elevation in salt accumulation in soils has been reported by many authors, including Funakawa *et al.* (2000), Haruyama *et al.* (2006), Funakawa and Kosaki (2007), Li *et al.* (2007), Sugimori *et al.* (2008), Zheng *et al.* (2009) and Moral *et al.* (2010). However, there is limited information on the influence of minor differences in elevation (on the scale of centimeters to decimeters) on soil salinization, especially for saline soils adjacent to lagoons, such as those in the Thua Thien Hue region.

To develop solutions to limit the unfavorable effects of soil salinization and promote rice production, we examined the spatial distribution and temporal variability of soil salinity in paddy fields, in which there are small differences in elevation, and evaluated the influence of elevation, electrical conductivity (EC) of soil saturation paste (ECe) and electrical conductivity of soil solution on the fields (ECw), and soil properties on rice yield (production).

## MATERIALS AND METHODS

### Study site

The research site was located in the Quang Phuoc commune (N16°35′, E107°32′), which is located in the Quang Dien district, Thua Thien Hue province, in the north central coastal region of Vietnam (Fig. 1). The commune is 14 km northeast of the city of Hue, stretching about 5 km along the Tam Giang lagoon, and has a flat landscape. People in this commune started to cultivate rice and other crops for living in the sixteenth century (Dan *et al.* 2006). The total area is 1048 ha, of which 509.3 ha is agricultural land, 161.4 ha is shrimp farming, 367.3 ha is non-agricultural land and 10 ha is unused land (Dan *et al.* 2006). There are two main irrigation rivers (Dien Hong and Bao Kho) that supply fresh water for the cultivation of rice and other crops. The dike stretching along the lagoon was constructed in 1994 to 1995 to prevent seawater intrusion from the lagoon into the land. However, there are some sections of the dike that haven't yet been constructed, because of financial constraints (Fig. 1).

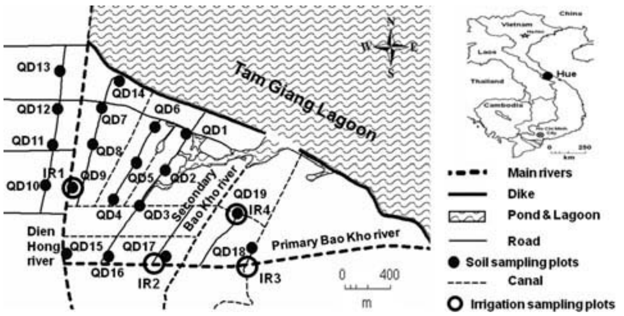


**Figure 1** Location of 19 research plots in the Quang Phuoc commune.

The average temperature and precipitation of the studied site in the 3 years from 2011 to 2013 are shown in Fig. 2. The climate of this region is tropical monsoon with two distinct seasons, dry (from April to August) and rainy (September to December). Annually, this region receives a large amount of precipitation; the total precipitation amounts in 2011, 2012 and 2013 were 4540,

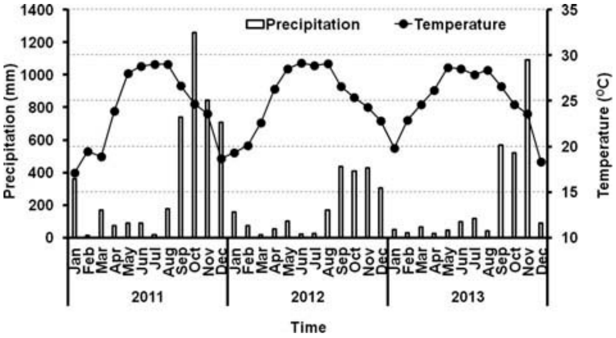


**Figure 2** Precipitation and temperature of research site from 2011 to 2013.

2190 and 2730 mm, respectively. Because precipitation is unevenly distributed over the months and is mainly focused in the period of September to December, this area is flooded annually during this time. The temperature increases gradually from January to May, then stays stable around 28 to 29°C during May to August (the hottest period of the year), then decreases until the end of the year.

Rice fields in the central part of the research site (QD2, 3, 4 and 5), along the lagoon (QD1, 6 and 14) and along the secondary Bao Kho river (QD17 and 19) (Fig. 1) always have water on the surface. Water table levels are about 10 to 60 cm during January to August and about 60 to 200 cm during September to December (flooding time). In the areas along the two main irrigation rivers of IR1 and IR2 (QD7, 8, 9, 10, 11, 12, 13, 15, 16 and 18), there is no water on the surface of the fields from late April to the middle of May and from the middle of July to late August. Water table levels are about 40 to 60 cm from September to December and about 20 to 30 cm during the rest of the time.

## Rice cropping calendar

There are two rice cropping seasons: winter–spring cropping lasts from January to May and summer–autumn cropping from May to September. Because Quang Phuoc commune is usually flooded in the rainy season (from the end of September to the end of December), there is no rice cultivation during this period because of water submergence (Dan *et al.* 2006).

# EXPERIMENTAL DESIGN

Experiments were conducted on 19 plots (QD1–QD19) that were distributed widely in the Quang Phuoc commune (Fig. 1). The distance between plots was approximately 400 m. To evaluate the influence of elevation on salinity distribution, the elevation of each point was measured by the static surveying technique with a handheld Global Navigation Satellite System (GNSS) receiver and field controller (GRS-1 GG, TOPCON, Tokyo, Japan) and computer software (GNSS-Pro, TOPCON, Tokyo, Japan) (one of the sampling plots was designated as an elevation of 0 m and the elevations of the 18 remaining plots were measured relative to this). To investigate the spatiotemporal variability of soil salinity, soil samples at the 19 plots were collected three times a year in both 2012 and 2013, from a depth of approximately 0–20 cm, using an auger. Soil sampling was conducted in January (after flooding and at the beginning of winter–spring cropping), in the middle of May (the transitional period between the winter–spring cropping harvest and the beginning of the sowing/transplanting time of the summer–autumn cropping), and in September (at the end of the summer–autumn cropping and prior to flooding). To measure the EC of the soil solution in the paddy fields (ECw), 19 porous cups (DIK-8390-11, Daiki, Japan) were installed in the 19 plots to collect soil solution samples at an interval of about 10 d (from February 2012 to September 2013) at a depth of approximately 20 cm from the soil surface. We didn't measure ECw from the end of September to the end of December, because all research plots were flooded during this period.

Irrigation water sampling was conducted three times in 2013 at almost the same time as soil sampling. The sample collection points were the same as the pump setting stations of the farmers. There were four sample collection points (sites IR1 through IR4); these were located at the Dien Hong River, the primary Bao Kho river section adjacent to QD17, the primary Bao Kho river section near QD18 and the canal adjacent to QD19, respectively (Fig. 1).

The rice yield of five representative square meters near each plot in the winter–spring and summer–autumn cropping seasons of 2013 was measured, and then averaged to examine the influences of elevation, salinity and major soil properties on rice production, including pH, cation exchangeable capacity (CEC), clay content, total carbon (C) and total nitrogen (N) contents.

# ANALYTICAL METHODS

Soil samples were air-dried, then crushed and passed through a 2-mm mesh sieve before analysis.

Particle size distribution was determined by a combination of pipette and sieving methods (Jackson *et al.* 1986). CEC and exchangeable cations were determined using the ammonium acetate (1 mol $L^{-1}$ and pH 7.0) method (Miller and Curtin 2006). Exchangeable cations $Na^+$ (sodium), $K^+$ (potassium), $Mg^{2+}$ (magnesium) and $Ca^{2+}$ (calcium) were determined by atomic absorption spectrophotometry (AA-700, Shimadzu, Kyoto, Japan). For CEC determination, residual soil was washed with 80% ethanol following ammonium acetate extraction; the remaining $NH_4^+$ (ammonium) was extracted with 10% NaCl (sodium chloride), and then determined by the Kjeldahl distillation method. Total C and total N contents in soils were determined using a dry combustion method with a CN analyzer (VarioMax CHN, Elementar, Germany).

One hundred grams of air-dried soil was mixed with 43 mL of deionized water (ratio 1:0.43) to prepare the saturation paste, which was used for the measurement of pH (pHe), ECe and concentrations of water-soluble cations and anions. The soil:water ratio of 1:0.43 was predetermined to satisfy the saturation paste criteria; these include the requirements that the soil paste should glisten and flow slightly when the container is tipped, and there is no free water accumulation on the surface after standing for at least 4 h (Miller and Curtin 2006). To compare the soil parameter values over time, the ratio of soil and water was fixed for all samples and for all soil collection times. pHe was determined using a glass electrode meter. ECe was measured with a conductivity meter (CM-30S, TOA Electronics Ltd, Tokyo, Japan). Water-soluble cations $Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$, and $NH_4^+$ and water-soluble anions $Cl^-$ (chloride), $SO_4^{2-}$ (sulfate), and $NO_3^-$ (nitrate) in the extracts were measured by high-performance liquid chromatography (LC-20AT, Shimadzu, Japan) equipped with a shim-pack IC-C3 for cations, a shim-pack IC-A1 for anions and a CDD-10A conductivity detector.

Because soluble cations may account for a substantial proportion of the extractable cations, exchangeable cations were calculated as the total extractable cations minus the concentration of soil solution (soluble) cations (United States Salinity Laboratory Staff 1954). To evaluate the hazards of sodium in solution, the sodium adsorption ratio (SAR) was calculated using the following formula:

$$\mathrm{SAR} = \left[\mathrm{Na}^+\right]/\left(\left[\mathrm{Ca}^{2+}\right] + \left[\mathrm{Mg}^{2+}\right]\right)^{0.5} \tag{1}$$

and the concentrations of $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ were presented in mmol $L^{-1}$ (Miller and Curtin 2006). The EC of irrigation water and ECw were measured with the conductivity meter.

The correlations between rice yield and elevation, ECe, pHe, CEC, clay content, total C and total N concentrations were analyzed using Sigma Plots 11 statistics software (SSI, San Jose, USA). Because the data for ECe wasn't normally distributed, the Spearman rank order correlation was applied for analyzing correlations between the yield and this parameter. Data of pHe, CEC, clay content, total C and total N was normally distributed; thus Pearson product moment correlation was used for analyzing correlations between the yield and these parameters.

# RESULTS

## Chemical composition of irrigation water

The chemical composition of irrigation water at the study sites is given in Table 1. pH was between 7.01 and 7.35. Although the irrigation water samples were collected at different times, the fluctuation in pH was small. The EC of IR4 in January and September and of IR3 in January were higher than those of the other locations: 0.38, 0.45 and 0.27 dS $m^{-1}$, respectively. Meanwhile, the EC of IR1 and IR2 was low in all seasons, ranging from 0.06 to 0.11 dS $m^{-1}$. Concentrations of major cations and anions occurred in

**Table 1** Cation concentrations, sodium adsorption ratios, pH and EC of water from four different irrigation rivers in the study area

| Collection date | Location | $Na^+$ | $K^+$ | $Mg^{2+}$ | $Ca^{2+}$ | $NH_4^+$ | $Cl^-$ | $NO_3^-$ | $SO_4^{2-}$ | SAR$^+$ | pH | EC | Irrigation water class$^{++}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ($mmol_c\ L^{-1}$) | | | | | | | | ($(mmol\ L^{-1})^{0.5}$) | | ($dS\ m^{-1}$) | |
| 21.Jan.13 | IR1 | 0.19 | 0.09 | 0.09 | 0.14 | 0.02 | 0.22 | 0.08 | 0.04 | 0.55 | 7.22 | 0.07 | C1–S1 Low salinity |
| | IR2 | 0.21 | 0.08 | 0.11 | 0.18 | 0.02 | 0.16 | 0.07 | 0.08 | 0.55 | 7.09 | 0.06 | C1–S1 Low salinity |
| | IR3 | 1.40 | 0.09 | 0.41 | 0.38 | 0.05 | 1.61 | 0.02 | 0.16 | 2.22 | 7.35 | 0.27 | C2–S1 Medium salinity |
| | IR4 | 2.25 | 0.09 | 0.54 | 0.25 | 0.06 | 2.71 | 0.02 | 0.28 | 3.58 | 7.19 | 0.38 | C2–S1 Medium salinity |
| 2.Jun.13 | IR1 | 0.13 | 0.04 | 0.10 | 0.15 | 0.00 | 0.24 | 0.02 | 0.04 | 0.37 | 7.31 | 0.09 | C1–S1 Low salinity |
| | IR2 | 0.19 | 0.04 | 0.11 | 0.15 | 0.00 | 0.13 | 0.02 | 0.05 | 0.54 | 7.01 | 0.06 | C1–S1 Low salinity |
| | IR3 | 0.20 | 0.05 | 0.12 | 0.16 | 0.00 | 0.28 | 0.02 | 0.07 | 0.53 | 7.32 | 0.09 | C1–S1 Low salinity |
| | IR4 | 0.17 | 0.04 | 0.10 | 0.15 | 0.00 | 0.17 | 0.02 | 0.05 | 0.47 | 7.16 | 0.07 | C1–S1 Low salinity |
| 11.Sept.13 | IR1 | 0.41 | 0.15 | 0.16 | 0.25 | 0.03 | 0.52 | 0.00 | 0.10 | 0.89 | 7.24 | 0.11 | C1–S1 Low salinity |
| | IR2 | 0.48 | 0.12 | 0.16 | 0.19 | 0.01 | 0.55 | 0.00 | 0.10 | 1.16 | 7.20 | 0.11 | C1–S1 Low salinity |
| | IR3 | 0.32 | 0.21 | 0.10 | 0.17 | 0.04 | 0.37 | 0.00 | 0.13 | 0.86 | 7.14 | 0.10 | C1–S1 Low salinity |
| | IR4 | 2.54 | 0.19 | 0.60 | 0.32 | 0.08 | 3.17 | 0.00 | 0.32 | 3.74 | 7.15 | 0.45 | C2-S1 Medium salinity |

IR1, IR2, IR3 and IR4 located at Dien Hong river, primary Bao Kho river section adjacent to plot QD17, primary Bao Kho river section near plot of QD18, and canal adjacent plot of QD19, respectively. $^+$ SAR: sodium adsorption ratio; $^{++}$ United States Salinity Laboratory Staff (1954).

the following order: $Na^+$, $Mg^{2+}$, $Ca^{2+}$ and $Cl^-$. Concentrations of $NH_4^+$ and $NO_3^-$ were negligible.

According to the criteria used to evaluate the quality of irrigation water based on EC and SAR (United States Salinity Laboratory Staff 1954), irrigation water at IR4 in January and September, and at IR3 in January, was classified as C2-S1 (EC from 0.25 to 0.75 dS $m^{-1}$ at 25°C and SAR from 0 to 10). The classification for the two main irrigation rivers of IR1 and IR2 was C1-S1 (EC from 0.10 to 0.25 dS $m^{-1}$ at 25°C and SAR from 0 to 10) in all seasons.

## Topography

Based on the values of relative elevations (Table 2) and ECe of 19 representative plots (Tables 3 and 4), the research site can be divided into low- and high-elevation plots. Soils that have an ECe higher than 1.9 dS $m^{-1}$ in at least one of the samples were in the low-elevation plots. In contrast, soils that have an ECe lower than 1.9 dS $m^{-1}$ in all the samples were in the high-elevation plots. An ECe of 1.9 dS $m^{-1}$ was used for the division, because rice growth starts to be influenced when ECe is higher than 1.9 dS $m^{-1}$ (Grattan *et al.* 2002). The low-elevation plots were in the central part of the research site (QD2, 3, 4 and 5), along the lagoon (QD1, 6 and 14) and along the secondary Bao Kho river (QD17 and 19), while the others surround the two main irrigation rivers of IR1 and IR2 (QD7, 8, 9, 10, 11, 12, 13, 15, 16 and 18) (Fig. 1). However, the difference between the high- and low-elevation plots was not large; relative elevation in the low-elevation plots was between –0.52 and 0.07 m, and that in the high-elevation plots was between 0.26 and 0.86 m.

## Physicochemical properties of soils

The physicochemical properties (Tables 2–4, Fig. 3) show that the fertility of these soils was very low, indicating that they were not suitable for rice growth. All the soils were high in sand and low in silt and clay; most soils were classified as sandy loam. CEC, total C and total N were low, from 2.0 to 6.4 $cmol_c$ $kg^{-1}$, 7.8 to 15.2 g $kg^{-1}$ and 0.8 to 1.6 g $kg^{-1}$, respectively. Most of the soils had a pHe from 4.0 to 6.0 (Fig. 3). In the low-elevation plots, pHe values in May and September were much lower than those in January, while in the high-elevation plots pHe was stable throughout the seasons. In soils at the low-elevation plots, the dominant exchangeable cations were $Mg^{2+}$ and $Ca^{2+}$, followed by $Na^+$ (Table 2). The exchangeable cation $K^+$ was low. In soils at the high-elevation plots, the dominant exchangeable cation was $Ca^{2+}$, followed by $Mg^{2+}$ and $Na^+$. The exchangeable cation $K^+$ was present in negligible concentrations. Because an increase in ECe and total soluble cations coincided with an increase in SAR, $Na^+$ was considered to be mainly responsible for salt accumulation in the surface paddy soils (Funakawa and Kosaki 2007 and Funakawa *et al.* 2000). Moreover, a highly significant positive correlation between the water-soluble cation $Na^+$ and water-soluble anion $Cl^-$ indicated the influence of NaCl from seawater on the ECe, ECw and total salt content (Haruyama *et al.* 2006). There were positive correlations between ECe and SAR, total cations and total anions. There were no correlations between ECe and pHe, clay content, CEC, total C and total N.

## Spatiotemporal variability of salinity in the surface soils

The spatial variability in ECe in the surface soils is shown in Tables 3–4 and Fig. 4–5, and temporal variability is shown in Tables 3–4 and Fig. 4 and 6. ECe and total soluble cation concentrations were high at low-elevation plots (Tables 3 and 4, Fig. 4). Compared with the high-elevation plots, ECe and ECw in the low-elevation plots were much higher. At the high-elevation plots, ECe was less than 1.0 dS $m^{-1}$. At the low-elevation plots (except for soils at QD17 in January 2012 and 2013 and September 2012, and QD19 in January and May 2012), ECe was larger than the threshold for rice growth of 1.9 dS $m^{-1}$ (Grattan *et al.* 2002). ECw in the high- and low-elevation plots increased gradually from January to September, though the increase was slight in the high-elevation plots (Fig. 6).

## Influences of salinity on rice production

The relationship between rice yield and ECe is shown in Fig. 7. The results demonstrate that rice yield in summer–autumn cropping was significantly negatively correlated with ECe ($r$ = –0.51, $P$ < 0.05), while a non-significant correlation was observed in winter–spring cropping. There was non-significant correlation between yield and elevation, pHe, clay content, CEC and total C and total N contents. Figure 7 also shows that rice yield in winter–spring cropping was much higher than in summer–autumn cropping.

# DISCUSSION

The EC of the two main irrigation water sources (IR1 and IR2) was low and stable throughout the year, being less than 0.1 dS $m^{-1}$ and classified as C1-S1 (United States Salinity Laboratory Staff 1954) (Table 1). This implies that IR1 and IR2 are not influenced by the

**Table 2** Elevation relative to QD1 and physicochemical properties of surface soils (0–20 cm) from the 19 plots in the study area (January 2012)

| Plots | | Elevation relative to QD1 | Sand | Silt | Clay | CEC | Exchangeable cations† | | | | Total C | Total N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $Na^+$ | $K^+$ | $Mg^{2+}$ | $Ca^{2+}$ | | |
| | | (m) | (%) | | | ($cmol_c\ kg^{-1}$) | ($cmol_c\ kg^{-1}$) | | | | ($g\ kg^{-1}$) | |
| Low-elevation plots | QD3 | −0.52 | 54 | 28 | 18 | 4.5 | 0.71 | 0.12 | 1.07 | 1.08 | 12.7 | 1.2 |
| | QD5 | −0.44 | 77 | 11 | 13 | 3.7 | 0.21 | 0.08 | 0.79 | 0.73 | 9.9 | 0.8 |
| | QD2 | −0.41 | 67 | 19 | 14 | 4.7 | 0.54 | 0.16 | 1.06 | 0.82 | 12.5 | 1.1 |
| | QD4 | −0.41 | 74 | 15 | 10 | 4.0 | 0.44 | 0.15 | 0.98 | 0.37 | 9.1 | 0.8 |
| | QD6 | −0.35 | 82 | 7 | 11 | 3.6 | 0.35 | 0.09 | 0.70 | 0.73 | 10.5 | 0.9 |
| | QD14 | −0.14 | 67 | 18 | 15 | 3.9 | 0.37 | 0.11 | 1.07 | 0.97 | 9.7 | 1.0 |
| | QD19 | −0.02 | 80 | 13 | 8 | 2.5 | 0.11 | 0.07 | 0.30 | 0.31 | 8.7 | 0.8 |
| | QD1 | 0.00 | 68 | 17 | 15 | 3.9 | 0.58 | 0.19 | 1.13 | 0.79 | 10.1 | 1.0 |
| | QD17 | 0.07 | 61 | 28 | 12 | 3.7 | 0.31 | 0.07 | 0.72 | 0.59 | 10.8 | 1.0 |
| High-elevation plots | QD16 | 0.26 | 44 | 42 | 14 | 5.5 | 0.15 | 0.05 | 0.44 | 0.77 | 10.9 | 1.0 |
| | QD18 | 0.26 | 44 | 40 | 16 | 4.0 | 0.14 | 0.07 | 0.38 | 0.65 | 15.2 | 1.6 |
| | QD15 | 0.28 | 45 | 39 | 15 | 6.4 | 0.10 | 0.05 | 0.09 | 0.35 | 13.5 | 1.4 |
| | QD7 | 0.37 | 34 | 40 | 26 | 4.9 | 0.11 | 0.10 | 0.22 | 0.73 | 12.7 | 1.4 |
| | QD8 | 0.42 | 58 | 26 | 17 | 3.0 | 0.04 | 0.06 | 0.04 | 0.32 | 11.1 | 1.2 |
| | QD9 | 0.73 | 27 | 57 | 16 | 6.4 | 0.14 | 0.10 | 0.21 | 0.54 | 10.3 | 1.0 |
| | QD10 | 0.75 | 69 | 19 | 12 | 2.9 | 0.06 | 0.06 | 0.04 | 0.71 | 12.0 | 1.3 |
| | QD11 | 0.81 | 69 | 20 | 12 | 3.6 | 0.09 | 0.10 | 0.07 | 0.93 | 12.1 | 1.3 |
| | QD13 | 0.84 | 70 | 21 | 9 | 2.0 | 0.04 | 0.07 | 0.03 | 0.37 | 8.1 | 0.8 |
| | QD12 | 0.86 | 73 | 18 | 9 | 2.2 | 0.07 | 0.05 | 0.01 | 0.37 | 7.8 | 0.8 |

†This value have been subtracted from the water-soluble cation concentration.

**Table 3** Total cation concentrations and sodium adsorption ratios (SAR) in saturation paste prepared from surface soils (0–20 cm) from the 19 plots in the study area at different sampling times

| Plots | | Total anions ($cmol_c\ kg^{-1}$) | | | | | | SAR ($mmol\ L^{-1})^{0.5}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2012 | | | 2013 | | | 2012 | | | 2013 | | |
| | | 1. Jan | 27. May | 9. Sep | 21. Jan | 14. May | 4. Sep | 1. Jan | 27. May | 9. Sep | 21. Jan | 14. May | 4. Sep |
| Low-elevation plots | QD3 | 2.00 | 2.22 | 2.71 | 2.00 | 4.01 | 3.00 | 9.41 | 6.03 | 5.50 | 9.30 | 12.11 | 12.53 |
| | QD5 | 1.09 | 2.59 | 1.92 | 1.05 | 1.89 | 1.55 | 5.78 | 3.48 | 5.52 | 7.39 | 6.02 | 6.45 |
| | QD2 | 2.01 | 3.92 | 3.05 | 1.61 | 3.49 | 2.08 | 9.58 | 6.03 | 6.63 | 8.92 | 8.19 | 9.68 |
| | QD4 | 2.73 | 4.63 | 5.04 | 1.90 | 2.85 | 2.16 | 14.31 | 8.74 | 11.81 | 10.23 | 9.09 | 13.57 |
| | QD6 | 1.72 | 3.40 | 3.30 | 1.34 | 2.19 | 2.27 | 6.62 | 4.58 | 7.89 | 6.84 | 6.37 | 7.48 |
| | QD14 | 1.46 | 4.14 | 3.87 | 1.34 | 2.54 | 1.76 | 7.55 | 6.60 | 5.72 | 9.54 | 6.73 | 4.66 |
| | QD19 | 0.32 | 0.80 | 1.67 | 0.79 | 1.54 | 1.10 | 2.57 | 2.86 | 3.52 | 6.47 | 8.00 | 7.98 |
| | QD1 | 2.99 | 5.06 | 3.38 | 2.27 | 3.92 | 2.07 | 9.59 | 6.10 | 7.31 | 8.77 | 6.74 | 8.77 |
| | QD17 | 0.23 | 0.75 | 0.53 | 0.50 | 0.99 | 1.15 | 7.32 | 6.51 | 4.79 | 6.00 | 8.23 | 12.79 |
| High-elevation plots | QD16 | 0.18 | 0.22 | 0.31 | 0.14 | 0.44 | 0.35 | 2.20 | 1.93 | 1.53 | 3.18 | 2.09 | 2.85 |
| | QD18 | 0.12 | 0.18 | 0.18 | 0.12 | 0.30 | 0.23 | 2.02 | 1.02 | 1.05 | 1.88 | 1.64 | 1.75 |
| | QD15 | 0.11 | 0.15 | 0.06 | 0.10 | 0.20 | 0.16 | 2.63 | 1.34 | 0.76 | 1.89 | 1.28 | 1.57 |
| | QD7 | 0.08 | 0.20 | 0.09 | 0.04 | 0.21 | 0.14 | 1.43 | 1.04 | 0.85 | 1.05 | 1.13 | 1.30 |
| | QD8 | 0.08 | 0.14 | 0.12 | 0.06 | 0.16 | 0.07 | 0.75 | 0.53 | 0.80 | 1.29 | 0.99 | 1.04 |
| | QD9 | 0.10 | 0.06 | 0.09 | 0.07 | 0.13 | 0.08 | 1.57 | 0.96 | 1.27 | 2.20 | 1.42 | 1.64 |
| | QD10 | 0.09 | 0.28 | 0.19 | 0.07 | 0.27 | 0.26 | 0.90 | 0.57 | 0.52 | 0.75 | 0.67 | 0.90 |
| | QD11 | 0.14 | 0.16 | 0.19 | 0.09 | 0.22 | 0.20 | 1.57 | 0.60 | 0.55 | 0.52 | 0.62 | 0.40 |
| | QD13 | 0.09 | 0.11 | 0.15 | 0.08 | 0.16 | 0.20 | 0.77 | 0.74 | 0.71 | 1.90 | 1.34 | 1.83 |
| | QD12 | 0.11 | 0.09 | 0.15 | 0.05 | 0.12 | 0.11 | 1.64 | 0.68 | 0.36 | 0.49 | 0.39 | 0.71 |

**Table 4** ECe and total cation concentrations in saturation paste prepared from surface soils (0–20 cm) from the 19 plots in the study area at different sampling times

| | | ECe (dS $m^{-1}$) | | | | | | Total cations ($cmol_c$ $kg^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2012 | | | 2013 | | | 2012 | | | 2013 | | |
| Plots | | 1. Jan | 27. May | 9. Sep | 21. Jan | 14. May | 4. Sep | 1. Jan | 27. May | 9. Sep | 21. Jan | 14. May | 4. Sep |
| Low-elevation plots | QD3 | 4.26 | 4.14 | 4.69 | 4.48 | 7.08 | 6.60 | 1.73 | 2.12 | 2.43 | 2.00 | 3.86 | 3.18 |
| | QD5 | 2.22 | 4.49 | 3.51 | 2.62 | 3.81 | 3.38 | 0.95 | 2.57 | 1.69 | 1.16 | 1.76 | 1.54 |
| | QD2 | 4.16 | 6.68 | 5.13 | 3.84 | 6.06 | 4.45 | 1.74 | 3.53 | 2.69 | 1.60 | 2.99 | 2.22 |
| | QD4 | 5.16 | 8.35 | 9.11 | 4.45 | 5.31 | 4.86 | 2.34 | 4.31 | 4.21 | 1.91 | 2.49 | 2.31 |
| | QD6 | 3.53 | 5.57 | 5.68 | 3.50 | 4.32 | 3.39 | 1.48 | 3.14 | 2.86 | 1.36 | 1.95 | 2.28 |
| | QD14 | 3.10 | 7.34 | 5.57 | 3.43 | 4.56 | 3.31 | 1.42 | 3.88 | 3.82 | 1.58 | 2.21 | 1.68 |
| | QD19 | 1.01 | 1.75 | 2.39 | 2.00 | 3.39 | 2.31 | 0.29 | 0.75 | 1.41 | 0.69 | 1.40 | 0.96 |
| | QD1 | 6.20 | 8.16 | 6.23 | 4.89 | 6.74 | 5.99 | 2.66 | 4.50 | 2.91 | 2.22 | 3.57 | 2.94 |
| | QD17 | 0.87 | 1.94 | 0.98 | 1.56 | 2.32 | 2.99 | 0.28 | 0.77 | 0.54 | 0.41 | 0.99 | 1.05 |
| High-elevation plots | QD16 | 0.46 | 0.54 | 0.58 | 0.42 | 1.00 | 0.82 | 0.15 | 0.21 | 0.29 | 0.15 | 0.39 | 0.33 |
| | QD18 | 0.45 | 0.72 | 0.37 | 0.46 | 0.76 | 0.56 | 0.15 | 0.31 | 0.18 | 0.19 | 0.29 | 0.23 |
| | QD15 | 0.26 | 0.40 | 0.53 | 0.32 | 0.52 | 0.43 | 0.14 | 0.15 | 0.07 | 0.12 | 0.18 | 0.16 |
| | QD7 | 0.27 | 0.57 | 0.24 | 0.18 | 0.56 | 0.40 | 0.10 | 0.21 | 0.10 | 0.08 | 0.17 | 0.14 |
| | QD8 | 0.25 | 0.49 | 0.30 | 0.20 | 0.42 | 0.24 | 0.09 | 0.16 | 0.12 | 0.09 | 0.13 | 0.08 |
| | QD9 | 0.31 | 0.18 | 0.26 | 0.25 | 0.37 | 0.26 | 0.11 | 0.08 | 0.11 | 0.09 | 0.12 | 0.10 |
| | QD10 | 0.34 | 0.89 | 0.47 | 0.45 | 0.69 | 0.62 | 0.13 | 0.37 | 0.24 | 0.20 | 0.26 | 0.26 |
| | QD11 | 0.64 | 0.68 | 0.56 | 0.44 | 0.63 | 0.55 | 0.30 | 0.30 | 0.27 | 0.18 | 0.23 | 0.20 |
| | QD13 | 0.36 | 0.39 | 0.37 | 0.28 | 0.44 | 0.42 | 0.11 | 0.15 | 0.15 | 0.11 | 0.14 | 0.17 |
| | QD12 | 0.35 | 0.41 | 0.38 | 0.25 | 0.37 | 0.33 | 0.14 | 0.16 | 0.16 | 0.10 | 0.10 | 0.11 |

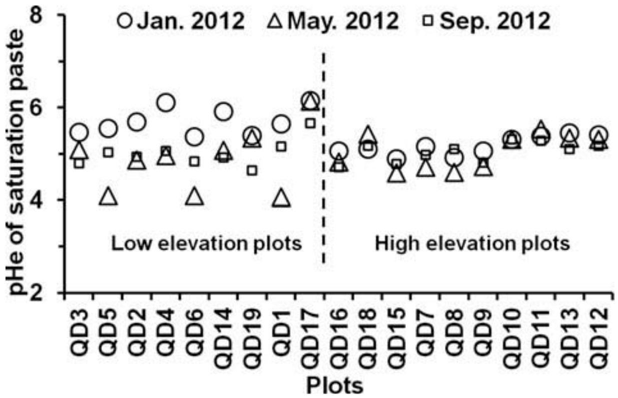


**Figure 3** pHe of saturation paste of 19 research plots in 2012.

intrusion of seawater. Therefore, IR1 and IR2 water can be used for the irrigation of most crops and soils with little risk of causing harmful levels of salinity and exchangeable sodium (United States Salinity Laboratory Staff 1954). Because IR3 and IR4 are located adjacent to the secondary Bao Kho river that connects directly to the lagoon (Fig. 1), seawater from the lagoon easily seeps into these two irrigation sources. As a result, the EC of IR3 (in January) and IR4 (in January and September) was medium level (0.27, 0.38 and 0.45 dS $m^{-1}$, respectively) and classified as C2-S1 (United States Salinity Laboratory Staff 1954). However, the EC of IR3 and IR4 was low (less than 0.1 dS $m^{-1}$) in the beginning of June; because the beginning of June is the beginning of the second rice cropping season, farmers take extra care to ensure the sluice gates are closed to prevent seawater intrusion during this period. Irrigation water sources IR3 (in January) and IR4 (in January and September) are classified as C2-S1; thus, they can also be used for the irrigation of crops and soils with a moderate amount of leaching occurring.

ECe and total soluble cation concentrations were high at the low-elevation plots (Fig. 4). This indicates that there is insufficient leaching of salts or salt re-accumulation in the low-elevation plots. Compared with ECe and ECw in the high-elevation plots, ECe and ECw in the low-elevation plots were much higher. In the low-elevation plots, ECe and ECw were higher than 1.9 dS $m^{-1}$ in all seasons (except for ECe at QD17 in January 2012 and 2013 and September 2012, and at QD19 in January and May 2012) (Tables 3 and 4, Fig. 4 and 6a), indicating the intrusion of seawater from the lagoon into these plots. There are dense canals and ponds that connect directly to the lagoon (Fig. 1) and are flooded annually from September to December in the depressed region; seawater therefore easily inundates the inland area via the canals and ponds at the time of rising tide or during flooding. In the high-elevation plots, ECe values were low and less than 1.0 dS $m^{-1}$ (Tables 3 and 4, Fig. 4), indicating that soils in these plots weren't invaded by seawater. The high-elevation plots are located along the two main irrigation rivers of IR1 and IR2; therefore, these plots are supplied frequently with freshwater with low salinity (Table 1). Though the relative elevation measurements (Table 2) indicate that the differences in elevation between the 19 plots were very small (tens of

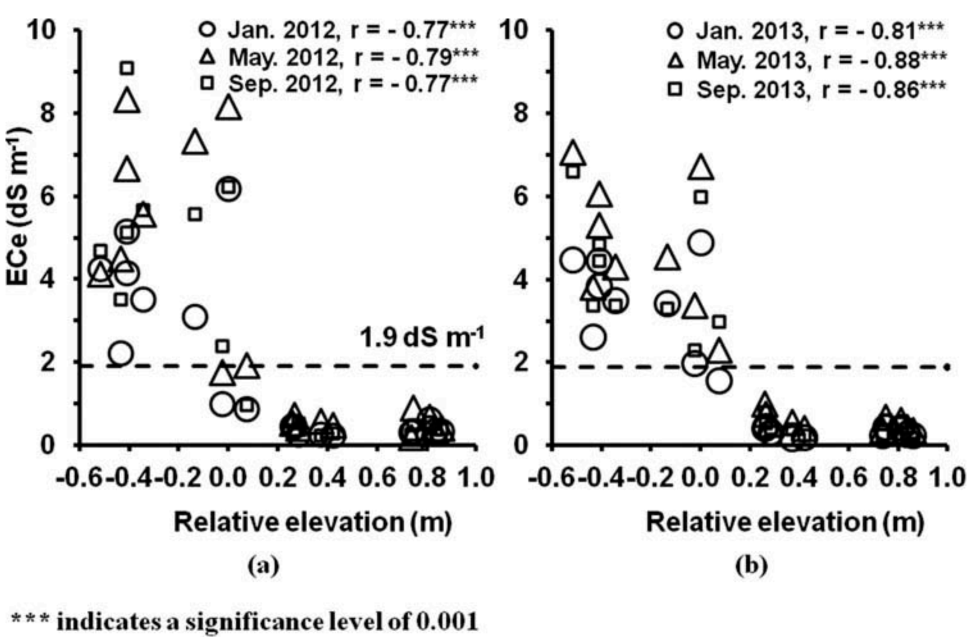


**Figure 4** Relationship between ECe of saturation paste and relative elevation (a) in 2012 and (b) in 2013.

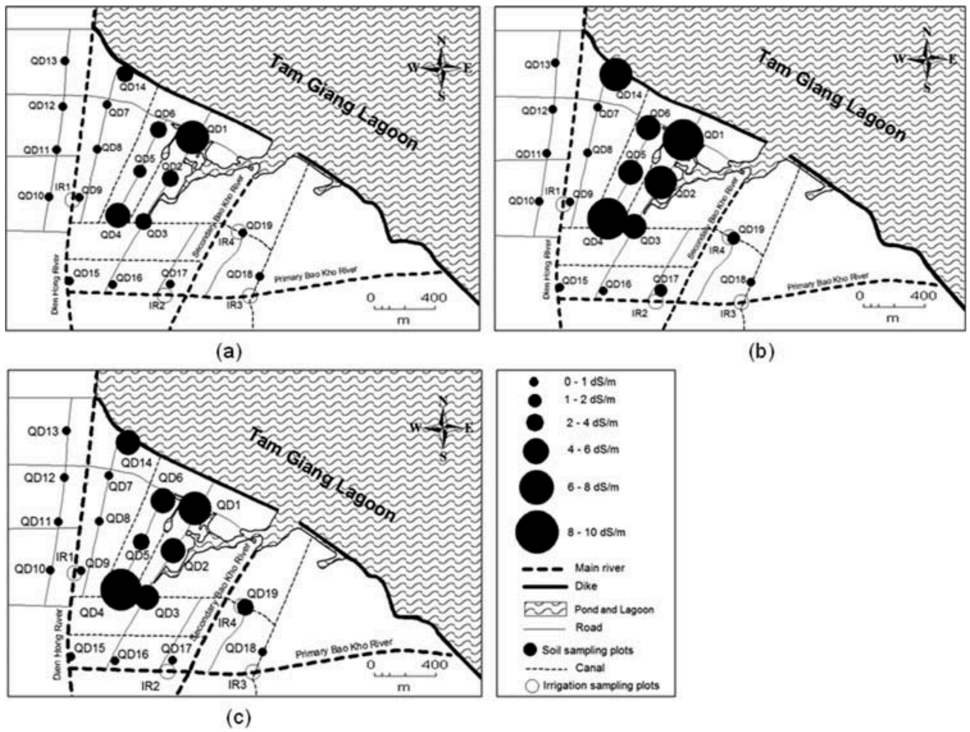


**Figure 5** Distribution of salinity of saturation paste (ECe) in (a) January, (b) May and (c) September 2012.

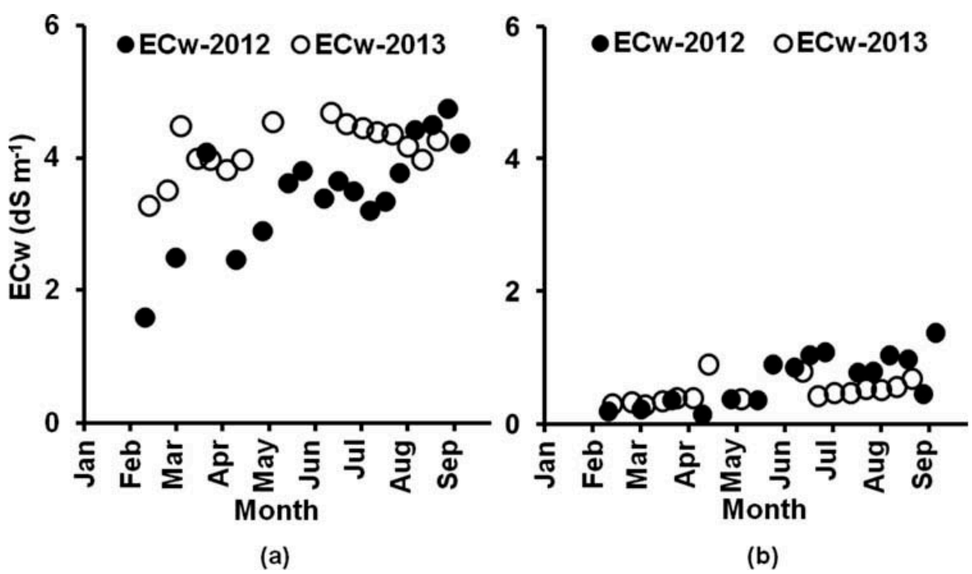


**Figure 6** Temporal variability of ECw of soil solution throughout the year at (a) the low elevation plot QD3 and (b) the high elevation plot QD10.

centimeters), they still led to large differences in soil salinity levels (Fig. 4–6). Thus, salt accumulation was strongly influenced by elevation. The influences of elevation on salinity accumulation have also been reported by Funakawa and Kosaki (2007), Sugimori *et al.* (2008) and Moral *et al.* (2010); Grattan *et al.* (2002) suggested that if the ECe of soil is greater than 1.9 dS $m^{-1}$, rice growth (production) starts to be adversely affected.

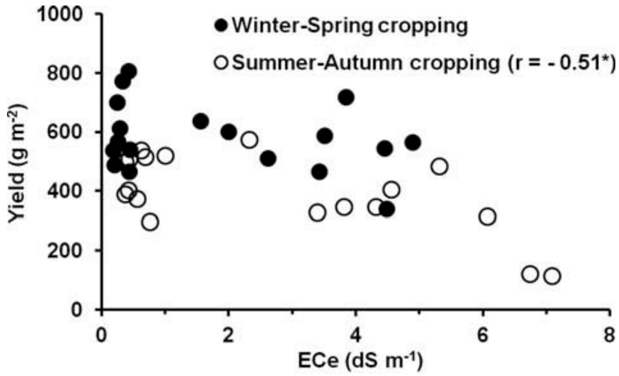


**Figure 7** Relationship between rice yield and ECe of saturation paste.

Thus, rice growth (production) in the low-elevation plots (except for soils at QD17 in January 2012 and 2013 and September 2012, and at QD19 in January and May 2012) were adversely affected by salinity, because ECe and ECw at these plots were much higher than 1.9 dS $m^{-1}$ (Tables 3 and 4, Fig. 4 and 6a). In contrast, rice growth (production) in the high-elevation plots wasn't affected by salinity, because ECe and ECw were much lower than the threshold of 1.9 dS $m^{-1}$ (Tables 3 and 4, Fig. 4 and 6b).

Besides being influenced by elevation, soil salinity also varied seasonally. ECe and ECw from May to September were much higher than in January, and the differences in ECe and ECw between May and September were small (Tables 3 and 4, Fig. 5 and 6). Because the flood or rainy season ends at the beginning of January, and the hot season with higher temperature and surface water evaporation occurs from May to September, salt concentrations in soils were diluted by high amounts of fresh water supplied by flooding in January, and became more condensed from May to September.

Rice yield in the summer–autumn cropping season tended to be lower than in the winter–spring cropping season (Fig. 7). These results may be caused by high ECe and ECw in the summer–autumn cropping season (May 2013) (Fig. 4 and 6). Rowell (1994) and Ghafoor *et al.* (2004) suggested that soil salinity directly affects rice growth through osmotic stress and anionic toxicity caused by $Na^+$, $Cl^-$ and $SO_4^{2-}$, which may also promote imbalances in rice nutrient metabolism. The negative correlations between yield and ECe were also reported by Sugimori *et al.* (2008).

In conclusion, though the differences in relative elevations between the 19 plots were very small (tens of centimeters), they can lead to large differences in soil salinity. Elevation and ECe measurements show that the research site could be divided into low- and high-elevation plots. The low-elevation plots were located in the central part of the research site, along the lagoon and along the secondary Bao Kho river, and the high-elevation plots surrounded the two main irrigation rivers. ECe and ECw in the low-elevation plots were much higher than in the high-elevation plots. In the high-elevation plots, soils were irrigated by freshwater with low EC, and not subject to seawater intrusion; thus, ECe and ECw were low throughout the year. Because ECe levels were much lower than the threshold for rice growth of 1.9 dS $m^{-1}$, rice growth (production) wasn't influenced by salinity. However, soils had poor fertility, as indicated by the low pHe, CEC, total C and total N; soil fertility is therefore also considered one of the main factors limiting rice production in the high-elevation plots. In the low-elevation plots, soils were subject to seawater intrusion; thus, their ECe was much higher than the threshold for rice growth of 1.9 dS $m^{-1}$. Moreover, soils also had poor fertility; hence, rice yield (production) at the low-elevation plots was influenced not only by high salinity but also by low soil fertility. ECe and ECw from May to September were the highest in the year.

Based on these results, some solutions are recommended to limit the unfavorable effects of soil salinization and promote rice yield. First, a dike with sluice gates stretching along the lagoon was constructed from 1994 to 1995 to prevent saltwater intrusion from the lagoon onto land; however, there are some sections of the dike that haven't yet been constructed because of financial constraints. Therefore, a complete dike system has to be constructed along the lagoon to completely prevent seawater intrusion into land. Second, because there are difficulties associated with draining in the depressed plots, it is necessary to construct adequate drainage facilities to promote the rapid drainage of water into the canals during and after flooding and irrigation in these plots. Third, because ECe and ECw increase from May to September, adequate fresh water for irrigation should be supplied frequently for the rice fields to lower ECe and ECw during this period. In addition, the irrigation fresh water quantity in the rivers must be provided appropriately to push back saltwater intrusion from the lagoon; thus, famers can use fresh water for their fields. Fourth, since soil fertility was poor with low organic matter content and low pHe, application of organic fertilizers and lime should be repeated annually over a long time period (Corwin and Lesch 2003). Finally, regarding improving rice breeding: at present, farmers in the Quang Phuoc commune are cultivating the local rice varieties 4B, KD and TH5, which have low salt-tolerant capacity and low yield. Hence, to increase rice yield and income, these local varieties need to be replaced with better-quality varieties (high salt-tolerant varieties).

## ACKNOWLEDGMENTS

The authors thank Engr. Khang Trong Hoang (Technician of Crop Science Laboratory, Hue University of Agriculture and Forestry) for his support during the survey.

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