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Variability of pH and EC of Selected Rice Cultivated Soils of Sri Lanka

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ABSTRACT

Soil pH and electrical conductivity (EC) are two major chemical properties affecting nutrient availability and rice grain yield. Therefore, this study was conducted to investigate the variation of pH and EC in the topsoil layer (0-15 cm) of rice fields as affected by major water source used for rice cultivation, rice-based cropping system adopted and rice growing soil orders in different agro-climatic zones (ACZs) in Sri Lanka. A total of 998 soil samples were collected from lowland rice fields. Both pH and EC were measured in 1:5 soil: water extracts. The pH of soil samples was in the range of 3.0-7.7 with a mean value of 5.0. Moreover, 75% of the soil samples had pH values below the optimum range for rice cultivation (5.5-7.0). Values of pH observed in Dry Zone soils were higher (5.2) than those in Wet Zone (4.4). Soil EC values ranged between 1.0 - 3,100 μScm^{-1} with a mean value of 148.5 μScm^{-1} . Soil EC was similar among climatic zones ($P>0.05$). Upcountry Intermediate zone recorded the highest soil EC than that in other ACZs ($P<0.05$). Moreover, 73%, 22%, 3%, 2% and 0.1% of soil samples recorded EC values in the ranges of less than 150 (non-saline), 150-400 (slightly saline), 400-800 (moderately saline), 800-2000 (highly saline) and more than 2000 (very highly saline) μScm^{-1} , respectively. Considering micro (e.g. paddy track) and macro (e.g. ACZ) scale spatial heterogeneity in soil pH and EC, appropriate site-specific strategies need to be adopted to improve soil pH and EC to suit sustainable rice crop production.

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INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food crop for Sri Lankans and serves as a vital source of mineral elements to consumers (Liyanarachchi *et al.*, 2020; Wijesinghe and Nazreen, 2020). Rice crop is mostly cultivated under submerged or alternate wetting and drying conditions that could create anoxic or reduced soil conditions. These conditions affect soil biological, physical and chemical properties (Najafi, 2013; Guo *et al.*, 2018). Among the soil's chemical properties, soil pH and electrical conductivity (EC) are two important variables that widely fluctuate with soil moisture content, thus affecting the productivity of rice crop (Rathnayake *et al.*, 2015a).

Most of the rice cultivated lands (>75%) in Sri Lanka are situated in the Dry and Intermediate zones, and most of those lands receive supplementary irrigation unless rainfall provides an adequate amount of water for rice cultivation (Kadupitiya *et al.*, 2021). Since evaporation is high in these areas, supplementary irrigation enhances the accumulation of salts such as calcium (Ca), sodium (Na) and magnesium (Mg) carbonates. These carbonates change soil pH and EC by combining with H^+ , therefore lowering soil acidity (Premawardhana *et al.*, 2015). Moreover, some of the rice lands are located closer to the seacoast where saltwater intrusion and an increase in soil EC are possible (Rathnayake *et al.*, 2015b). Seawater contains high concentrations of NaCl, Na_2SO_4 , $MgSO_4$, $CaSO_4$, $MgCl_2$, KCl and Na_2CO_3 salts (Rengasamy, 2002, Munns *et al.*, 2008; Feng *et al.*, 2018). Soil EC is related to total soluble ions either cations (Ca^{2+} , Mg^{2+} , K^+ , H^+ , Na^+) or anions (NO_3^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} , Cl^-) in the solution (Smith and Doran, 1996; Kekane *et al.*, 2015).

Rice cultivation under submerged or flooded conditions is a usual practice. This creates oxygen deprivation and therefore, affects the soil's chemical properties significantly (Taylor *et al.*, 2011). During the oxidation-reduction processes, H^+/OH^- ions are consumed/produced thus it increases pH in acidic soil and decreases pH in alkaline soil under flooded conditions (Ponnamperuma,

1972; Patra and Mohanty, 1994; Fageria *et al.*, 2011). Solubility and availability of nutrients, soil microbial growth and their activities are important biogeochemical processes affected by soil pH (Gentili *et al.*, 2018; Neina, 2019). For example, micronutrient uptake is more favoured under acidic soil conditions than under neutral-alkaline conditions (Gentili *et al.*, 2018). Soil pH also affects the availability of major soil nutrients for rice plants including nitrogen (N) and phosphorus (P) (Cheng *et al.*, 2017). Furthermore, soil pH influences the translocation and recycling of nutrients and toxic trace elements in soil (Neina, 2019). The desirable pH for optimal plant growth varies among different crop species. For rice, the most favourable pH range is 5.5 -7.0 (Bandara, 2005; Rosmery *et al.*, 2017; Mandala *et al.*, 2021). The pH of rice-growing soils could be lowered due to the leaching of basic cations such as Ca, Mg, K and Na, weathering of minerals, application of fertilizers, producing carbonic acid through dissolving of CO_2 in soil water, accumulation of carboxyl and phenolic compounds, producing humic residues through soil organic matter inputs, acid rains and nitrification (Fageria *et al.*, 2002; White, 2005; Guo *et al.*, 2018; Neina, 2019).

Electrical conductivity measured in soil solution can be used as a salinity index. It reflects the concentration of dissolved salts in the soil solution. Higher EC values in the soil solution usually indicate higher salinity levels, which can affect water availability for plant uptake and potentially limit plant growth. Therefore, soil solution EC is a useful indicator for assessing soil salinity and its impact on water holding capacity, nutrient availability, and overall plant suitability (Rathnayake *et al.*, 2015; Gopalakrishnan & Kumar, 2020).

Based on the total annual rainfall, Sri Lanka is divided into three (3) climatic zones (CZs), Wet zone, Intermediate zone and Dry zone. The Dry zone receives mean annual rainfall of less than 1750 mm with a relatively dry period from June to September. Areas receiving mean annual rainfall greater than 2,500 mm are considered Wet zone. The Intermediate zone receives mean annual rainfall of 1750 mm to 2500 mm. Depending on the elevation, three elevation classes have been identified as Low country (less than 300 m), Mid country (300 -

900 m) and Upcountry (more than 900 m) (Punyawardena, 2010). Considering those climatic zones and elevation classes, seven (7) agro-climatic zones (ACZs) have been identified in Sri Lanka. Out of those, six ACZs are considered as main rice cultivating zones in the country i.e., Dry zone Low country (DL- consists of 378,000 ha paddy lands), Intermediate zone Low country (IL-47,800 ha), Intermediate zone Mid country (IM- 1640 ha), Intermediate zone Upcountry (IU- 630 ha), Wet zone Low country (WL- 17,450 ha) and Wet zone Mid country (WM- 365 ha) (Kumara and Karunathilaka, 2017; DOA, 2021).

Rice cultivation in Sri Lanka is practiced using water from three sources (i.e., major irrigation, minor irrigation and rainfed). A reservoir providing irrigation water to a command area greater than 80 ha is considered a major irrigation scheme whereas minor irrigation schemes have a command area less than 80 ha. Rice cultivation in DL and IL largely depends on both major and minor irrigation schemes as supplementary sources of irrigation while the dependency on rainfall increases in other ACZs (Imbulana *et al.*, 2006; Kumara and Karunathilaka, 2017). Once rainwater is received it is stored in tanks and provides water for agriculture through irrigation. Moreover, these reservoirs are positioned in a cascade system conveying water to downstream tanks through agricultural lands altering the quality of the irrigation water, including pH and EC. However, the situation is different in a closed and localized rainfed system. Therefore, knowing the effects of different water sources on soil pH and EC of rice fields is important in agronomic decision making.

To achieve high crop productivity in areas of water scarcity, rice is cultivated in rotation with different crops such as banana, vegetables and other field crops (OFC). Accordingly, several rice-based cropping systems have been identified in the country (i.e., rice-rice, rice-fallow, rice-banana, rice-OFC or rice-vegetables) (Malaviarachchi *et al.*, 2016; Kumara and Karunathilaka, 2017; Sirisena and Suriyagoda, 2018). Crop management practices can have a significant influence on soil quality parameters (Bai et al.

2018). Similarly, soil pH and EC of rice-based cropping systems in the country may have been affected due to the variation in crop management. Moreover, soils used to cultivate rice in Sri Lanka have different geological origins such as Alfisols, Entisols, Histosols, Inceptisols, Ultisols and Vertisols (Panabokke, 1978). These soil orders have their inherent physical and chemical characteristics. Therefore, the objective of this study was to examine the variation of soil pH and EC levels in farmer managed lowland rice fields in Sri Lanka as affected by major water source used for rice cultivation, rice-based cropping system adopted and different rice growing soil orders in different ACZ in Sri Lanka.

METHODOLOGY

Sample collection and processing

A total of 998 soil samples were collected from lowland rice fields belonging to three climatic zones (CZs), six agro-climatic zones (ACZs); DL, IL, WL, WM, IM and IU, and five soil orders (Fig. S1). The number of soil samples collected from each ACZ was proportional to the rice land extent in those ACZs (Table 1). Soil samples represented farmer fields receiving water from different sources, different rice-based cropping systems and different soil orders (Fig. S1). Selection of locations and collection of soil samples were made as described in Kadupitiya *et al.* (2021). One sample represented a composite sample obtained from a minimum of four locations in a rice track (*Yaya*) considering the field level heterogeneities. Each soil sample represented the top 0-15 cm soil layer and was collected using a soil auger. Soil samples were air dried, and debris were removed, homogenized and sieved using a 2 mm sieve. Samples were stored at room temperature in a dry and dark room until used for analysis. The CZ, ACZ, soil order, and water source used for rice cultivation relevant to the location of the soil samples collected were determined by overlaying Google map, ACZ map, soil order map, and water source map of Sri Lanka. The soil order map was generated using the information presented in Dassanayake *et al.* (2007), Dassanayake and Silva (2010a, 2010b), and Mapa (2020) and the generated map is presented in Fig. S1.

Measurement of soil pH and EC

In the laboratory, 10 g of soil was measured from each sample and mixed with 50 mL of distilled water, i.e., suspension method (Dharmakeerthi *et al.*, 2007). Samples were shaken for two hours in an orbital shaker at room temperature. After resting for 15 minutes, soil pH and EC were measured using a pH and EC meter (Eutech WC PC 650, Singapore). Two local/laboratory standard soil samples and two blanks were used in each batch (i.e., 36 soil samples) for internal quality control. Two soil samples which were air dried, gravel and other plant parts were removed, homogenized and sieved using a 2 mm sieve and tested for pH and EC as local/laboratory standards. As blanks, only the distilled water was added without adding soil. Moreover, pH and EC electrodes were calibrated daily using the manufacturer's standards (Eutech WC PC 650, Singapore).

Statistical analysis

To test the existence of spatial autocorrelation of pH and EC values in the tested data set, Moran's I test statistics were computed in ArcGIS software. Additional statistical analyses were performed using SAS 9.1 software. Analysis of Variance (ANOVA) was performed as a two-step process. First, the difference in pH and EC of soil samples among ACZs was determined using the General Linear Model procedure. In the second step, differences in pH and EC of soil samples among the water sources used, cropping systems adopted and soil orders, within each ACZ were tested using ANOVA. Three-factor factorial ANOVA was performed to determine the effects of major water sources used for rice cultivation, rice-based cropping systems adopted, rice growing soil orders and their interactions on soil pH and EC at each ACZ. The means were compared using Duncan's New Multiple Range Test (DNMRT). Statistical significances were expressed at $\alpha=0.05$.

RESULTS AND DISCUSSION

Soil pH and EC in rice soils

Moran's I test statistics for spatial autocorrelation of pH (Moran's Index: 0.12,

expected index: -0.001, Variance: 0.11, z-score: 0.36, p-value: 0.72) and EC (Moran's Index: 0.076, expected index: -0.001, variance: 0.09, z-score: 0.25, p-value: 0.80) indicated the randomness of pH and EC values in spatial scale. The pH of rice soil samples was in the range of 3.0 -7.7 with a mean value of 5.0 (Fig. 1). The optimum range of pH for rice cultivation is 5.5 to 7.0 (Bandara, 2005; Rosmery *et al.*, 2017; Mandala *et al.*, 2021), and 75% and 0.9% of soil samples had pH values below and beyond this range, respectively. Long-term application of inorganic fertilizers especially urea has been a key contributor to lower soil pH in different cropping systems. When urea is applied to the soil it is converted to ammonium and undergoes nitrification process. During nitrification, H^+ is released into the soil solution intensifying acidification (Liu *et al.*, 2013; Parvathi *et al.*, 2013; Cheng *et al.*, 2017; Nayakekorale *et al.*, 2020; Wang and Huang, 2021). In lowlands exposed to high annual rainfall such as WL, protracted submerged conditions can also be observed. This results in the dissolution and subsequent loss of most of the cations through runoff, erosion or deep percolation (Ponnamperuma, 1972; Gilkes & McKenzie, 1988; Liu *et al.*, 1990; Nadeem & Farooq, 2019). These are the major reasons for observing low levels of pH in most of the soil samples below the optimum range.

Soil EC values were in the range of 1.0 to 3,169 μScm^{-1} with a mean value of 148.5 μScm^{-1} (Fig. 1). About 73% of soil samples had EC values less than 150 μScm^{-1} , and those can be considered as very low level of salinity. Moreover, 22% of the soil samples were low saline (EC range 150-400 μScm^{-1}), 3% were moderately saline (EC range 400-800 μScm^{-1}), 2% were highly saline (EC range 800-2,000 μScm^{-1}), and 0.1% was very highly saline (EC more than 2,000 μScm^{-1}). Therefore, 2.1% of the soil samples used in the present study were under high and very-high salinity categories according to Hesse (1964).

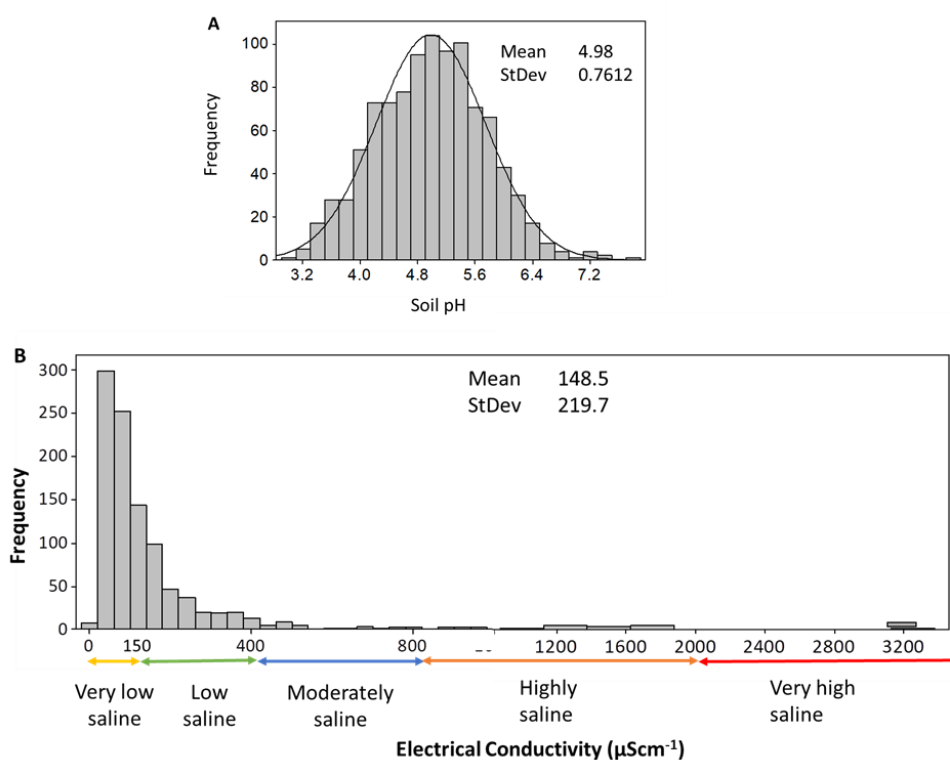


Figure 1. Distribution of pH (A) and EC (B) of rice soil samples collected from Sri Lanka.

Table 1. Soil pH and electrical conductivity (EC) in different agro-climatic zones (ACZs) and climatic zones (CZs)

ACZs	Soil pH	Soil EC ($\mu\text{S cm}^{-1}$)
Dry zone Low country (DL) (n=563)	5.2 \pm 0.03 ^a	163.2 \pm 9.52 ^b
Wet zone Low country (WL) (n=135)	4.3 \pm 0.05 ^d	131.7 \pm 13.58 ^b
Wet zone Mid country (WM) (n=21)	4.7 \pm 0.15 ^{bc}	97.1 \pm 18.38 ^b
Intermediate zone Low country (IL) (n=247)	4.9 \pm 0.05 ^{ab}	119.1 \pm 14.50 ^b
Intermediate Zone Mid country (IM) (n=17)	4.6 \pm 0.19 ^{dc}	140.7 \pm 22.41 ^b
Intermediate zone Up country (IU) (n=15)	5.1 \pm 0.17 ^a	316.6 \pm 101.76 ^a
CZs		
Dry zone (DZ) (n=563)	5.2 \pm 0.03 ^a	163.2 \pm 9.52 ^a
Intermediate zone (IZ) (n=279)	4.9 \pm 0.05 ^b	131.0 \pm 14.20 ^a
Wet zone (WZ) (n=156)	4.4 \pm 0.05 ^c	127.0 \pm 12.02 ^a

Values represent mean \pm standard error. Means followed by the same letter within a column are similar at $\alpha=0.05$. n=Sample size

Distribution of soil pH and EC in different ACZs and CZs in Sri Lanka

Top soil pH and EC are two key determinants of rice crop productivity, and those may be different among the CZs and ACZs of Sri Lanka. When comparing CZs, higher pH values were observed in DZ than those in WZ soils (Table 1). Out of the six cultivating ACZs, DL, IL and IU recorded higher pH values than those of WL, WM and IM (Table 1). The mean soil pH values

reported in DL and IU were higher than 5 ($P<0.05$). When comparing EC among CZs, similar soil EC values were recorded among CZs ($P>0.05$) (Table 1). Soil samples collected from IU recorded the highest EC values than that of other ACZs (Table 1). Several studies have reported that rice cultivated soils are highly modified through anthropogenic activities, creating temporal and spatial variation in chemical properties (Chandrajith *et al.*, 2005; Rosemary *et al.*, 2017; Rubasinghe

et al., 2021). Moreover, topography even within a narrow spatial scale, can also contribute to the variation in soil pH and EC (Liu et al., 2009; Vitharana et al., 2008; Rosemary et al., 2017). Therefore, apart from the observed variation of soil pH and EC among CZs or ACZs, those can also vary within a paddy track (Yaya or Catena) (Corstanje et al., 2007; Rosemary et al., 2017).

The DZ soils experience less leaching (Brady and Weil, 2008; Dassanayake et al., 2010c; Liu et al., 2012; Rosemary et al., 2017). Alfisols are the most abundant soil in DL (Indraratne, 2020). Special characteristics of Alfisols are clay illuviation in the B horizon and moderate to high base concentration being Ca^{2+} , and Mg^{2+} as dominant cations (Lynn et al. 2002; Indraratne, 2020). Vertisols are found in the north-western region in DL (Panabokke, 1996; Kumaragamage et al., 2010). Moreover, low precipitation and high evaporation in some months of the year, poor drainage during rainy season due to flat terrain, accumulation of basic cations from groundwater to soil surface and precipitation of those during dry season have accelerated the accumulation of salts in soil surface in DL (Schaetzl and Anderson, 2005; Liu et al., 2013; He et al., 2014; Vasak et al., 2015; Rosemary et al., 2017).

Low soil pH values observed in the WZ (WL and WM) can be due to several reasons. Leaching of basic cations such as K, Ca and Mg is high due to heavy rainfall occurring in these zones (Liu et al., 2013; Rathnayake et al., 2015a; Indraratne 2020; Nayakekorale et al., 2020). Ultisols are the most abundant soil order in WZ, and those have a high weathering and leaching rate under warm temperatures and high soil moisture availability (Indraratne, 2020). It has a poor performance in crop production due to the low values of soil fertility, EC, pH, CEC, base saturation, organic matter content and water-holding capacity (Indraratne, 2020; Purwanto et al., 2020). In order to overcome those constraints and improve productivity, the Department of Agriculture of Sri Lanka has recommended the application of inorganic and organic sources of fertilizers (DOA, 2021): Additionally, the application of high rates of both chemical (synthetic) fertilizers and organic matter is a common management practice in these

regions due to the wide practice of rice-vegetable crop rotation (Maraikar et al., 1997; Wickramasinghe et al., 2003; Weerasinghe, 2017).

In the present study, the average value of EC in the IZ (IL, IM, IU) was comparatively higher than the average value of WZ (WL and WM) and DZ (DL) (Table 1). Soils in the IU contain high amounts of soil organic matter due to the presence of a rice-vegetable cropping system (Maraikar et al., 1997; Wickramasinghe et al., 2003; Weerasinghe, 2017). Moreover, lower temperature in IU has also lowered the decomposition rate of organic matter than other rice growing ACZs. These reasons may have collectively influenced in creation of higher EC values in IU soils than in other ACZs.

Variation of soil pH as affected by cropping systems, soil orders and water sources

Among the three CZs, soil pH values in IZ were similar among the water source used, cropping system adopted or soil orders ($P>0.05$) (Table 2). However, soil pH values in DZ were affected by the interaction of water source used and soil order ($P<0.05$). Moreover, soil pH values in WZ were affected by soil orders and the interaction of cropping system and soil order ($P<0.05$) (Table 2).

Considering the six ACZs, soil pH values in WL, WM, IM and IU were not affected by the water sources used, cropping systems adopted or soil orders ($P>0.05$) (Table 2). However, soil pH values in DL were affected by the interaction of water sources used and soil orders ($P<0.05$), and that of IL differed among soil orders and was affected by the interaction effect of previous crop \times soil order ($P<0.05$) (Table 2).

Due to the presence of a significant interaction between the major water sources used for rice cultivation and soil orders in DL (Table 2), the pH of different soil orders was compared within each water source. In areas receiving water from major irrigation schemes and rainfall, soil pH values were similar among soil orders (Fig. 2). However, Entisols occurred in minor irrigation schemes recorded lower soil pH than Ultisols. Entisols commonly occur at the site of young alluvial, glacial, wind-blown deposits or in sand beds and show very little

profile development (Indraratne, 2020). Moreover, Entisols were observed under all three water sources. Therefore, the lower pH of Entisols observed under minor irrigation

would not be due to the water source alone and may be associated with some other unexplained source of variation. Therefore, this needs further experimentation.

Table 2. Statistical significance of different sources of variability on soil pH in different agro-climatic zones (ACZ), and Climatic zones (CZ)

Sources of variability	ACZ					CZs			
	DL (563)	WL (135)	WM (21)	IL (247)	IM (17)	IU (15)	DZ (563)	IZ (279)	WZ (156)
Major water Source used	NS	NS	NS	NS	NS	NS	NS	NS	NS
Previous crop	***	NS	NS	NS	NS	NS	***	NS	NS
Soil orders	NS	NS	NS	**	NS	NS	NS	NS	**
Water source × Previous crop	NS	NS	ND	NS	ND	ND	NS	NS	NS
Water source × Soil order	**	NS	NS	NS	ND	ND	**	NS	NS
Previous crop × Soil order	NS	NS	NS	*	ND	ND	NS	NS	*
Water source × Previous crop × Soil order	NS	NS	ND	NS	ND	ND	NS	NS	NS

*, ** and *** represent the statistical significance at 0.05, 0.01 and 0.001, respectively, ND=Not detected, NS = Not significant, n=sample size, values within the parenthesis are sample sizes. (DZ-Dry Zone, IZ-Intermediate Zone, WZ-Wet Zone, DL- Dry zone Low country, WL- Wet zone Low country, WM- Wet zone Mid country, IL- Intermediate zone Low country, IM- Intermediate zone Mid country, IU- Intermediate zone Upcountry).

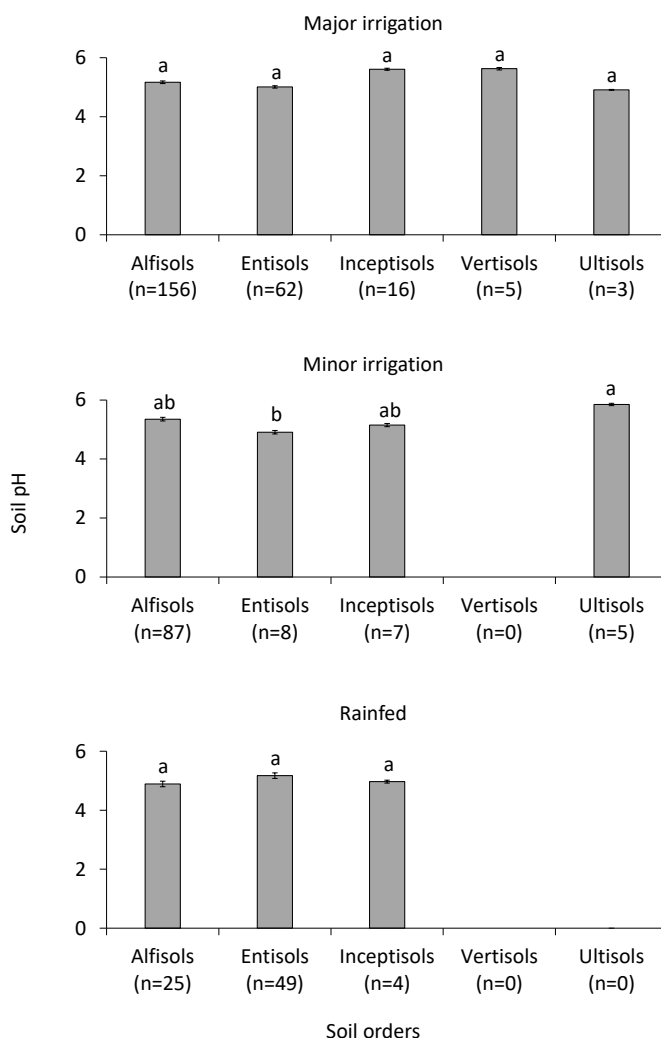


Figure 2. Variation of pH in rice-cultivated soil orders as affected by major irrigation, minor irrigation and rainfed systems in the Dry zone Low country of Sri Lanka. Vertical lines represent the standard error (S.E) of the means. Bars followed by the same letters are not significantly different at P=0.05. n= sample size

The observed variation in soil pH among the water sources used, cropping systems adopted and soil orders within each ACZ indicates that the land-use and crop management practices adopted for a long period have contributed to alter soil pH and EC apart from the inherent soil characteristics. The key anthropogenic activities include land preparation, fertilizer applications, and irrigation methods adopted (Chandrajith *et al.*, 2005b; Fageria *et al.*, 2011; Rathnayake *et al.*, 2017b; Rosemary *et al.*, 2017; Balasooriya *et al.*, 2021; Rubasinghe *et al.*, 2021).

When the interaction effect of previous crop and soil orders in IL was considered (as stated in Table 2), Histosols recorded a lower pH (3.5) than Ultisols and Alfisols in the rice-rice cropping system. Histosols are developed from the lake, lagoon, and marine deposits and are in the lowest part of the catena under poorly drained conditions. These conditions create lower pH (Indraratne, 2020). Previous studies have revealed that rice-fallow cropping system created low soil pH due to the accumulation of organic acids and microbial respiration during the decomposition of crop residues, especially rice straw (Neugschwandtner *et al.*, 2014; Vasak *et al.*, 2015; Ovung *et al.*, 2021). Rathnayake *et al.* (2017) reported high pH values in the root zone (top 15 cm) of the rice-rice cropping system compared to rice-soybean, rice-tobacco or rice-onion rotations in Alfisols of DZ of Sri Lanka. The rice-rice system mostly found in the lower part of the catena experiences long-term submerged/anoxic conditions which consume protons during the reduction process. Moreover, the rice-rice cropping system increases organic matter content in soil due to the retention of more crop residues in the field than rice-soybean, rice-tobacco or rice-onion rotations. Organic matter which is sourced from rice stubble decomposes slowly due to the creation of anaerobic condition with long term submergence (Rathnayake *et al.*, 2017). Therefore, the differences in soil pH observed among cropping systems would also be associated with the position in the landscape these cropping systems are located. The results of the present study are not in agreement with Rathnayake *et al.* (2017) which could be due to differences in sampling

times. In the present study, soil samples were taken between the two cultivating seasons whereas samples were taken during the cropping season in the study by Rathnayake *et al.* (2017).

Variation of soil EC as affected by cropping systems, soil orders and water sources

When considering CZs, soil EC values of IZ were not affected by the water source used, cropping system or soil order ($P > 0.05$). However, EC values of DZ were affected by the interaction of water source and soil order ($P < 0.05$). Moreover, in WZ, soil EC values were affected by soil orders and the interaction of cropping system and soil order ($P < 0.05$) (Table 3). When considering ACZs, soil EC values in DL differed among previously cultivated crops ($P < 0.05$) (Table 3). However, soil EC values in WL, IL, IM, and IU were not affected by the water sources used, cropping systems adopted or soil orders ($P > 0.05$). Higher order interactions and main effects were significantly affected to determine the EC values in soil samples collected from WM. In DL, Vertisols recorded higher EC values ($446.5 \mu\text{Scm}^{-1}$) than other soil orders ($P < 0.05$) (Fig. 3). In WM, rice fields receiving water from minor irrigation schemes recorded higher soil EC values ($142 \mu\text{Scm}^{-1}$) than those receiving water only from rainfall ($64 \mu\text{Scm}^{-1}$) (Fig. 4). Previously vegetable cultivated rice fields recorded higher soil EC values than other rice-based cropping systems adopted in WM (Fig. 4). Moreover, Ultisols recorded the highest soil EC ($1,873 \mu\text{Scm}^{-1}$) than other soil orders in the WM.

Relationships between soil pH and EC

As pH is the measurement of H^+ and EC is a non-specific measurement of the concentration of both positively and negatively charged ions in a sample, the possibility of explaining the relationship between pH and EC would aid in making agronomic and crop management decisions. When all the soil samples collected were considered there was a weak significant correlation between soil pH and EC values ($r = 0.15$, $P < 0.001$) (Fig. 5). When the correlation between soil pH and EC within each CZ was studied, a weak positive

correlation was observed in DZ ($r=0.19$, $P<0.0001$) and WZ ($r=0.25$, $P<0.0015$) (Table 4). The estimated change of EC per unit change of pH was in the range of 45 and 59 μScm^{-1} . When ACZs were considered, positive correlations between soil pH and EC were observed for DL and WL (Table 4). The estimated change of EC per unit change of pH was in the range of 61 and 75 μScm^{-1} . Among the water sources used, only rainfed systems had a significant correlation between soil pH and EC ($r=0.35$, $P<0.0001$) (Table 4).

Among the soil orders tested, EC increased in the range of 28-74 μScm^{-1} per unit increase in pH for Alfisols, Entisols, and Ultisols. Moreover, the same for Vertisols was 1199

μScm^{-1} and that of Inceptisols was 134 μScm^{-1} . This would be due to the high base saturation and high buffering capacity of Vertisols (Indraratne, 2020). Out of different crop rotations, rice-rice and rice-fallow rotations had a significant positive increase ($P<0.05$) in EC in the range of 33-58 μScm^{-1} while rice-vegetable and rice-OFC rotations had no significant relationships between pH and EC ($P>0.05$). For most of the upland cropping systems, a negative relationship between soil pH and EC was reported (Brckner 2012; Aini et al., 2014; Aizat et al., 2014; Mazur et al., 2022), and only limited information is available for rice (Hossain et al., 2015).

Table 3. Statistical significance of different sources of variability on soil EC in different agro-climatic zones (ACZ), and Climatic zones (CZ)

Sources of variability	ACZs						CZs		
	DL (563)	WL (135)	WM (21)	IL (247)	IM (17)	IU (15)	DZ (563)	IZ (279)	WZ (156)
Major water source used	NS	NS	***	NS	NS	NS	NS	NS	NS
Previous crop	NS	NS	**	NS	NS	NS	***	NS	NS
Soil order	***	NS	**	NS	NS	NS	NS	NS	**
Water source × Previous crop	NS	NS	ND	NS	ND	ND	NS	NS	NS
Water source × Soil order	NS	NS	***	NS	ND	ND	**	NS	NS
Previous crop × Soil order	NS	NS	***	NS	ND	ND	NS	NS	*
Water source × Previous crop × Soil order	NS	NS	ND	NS	ND	ND	NS	NS	NS

*, ** and *** represent the statistical significance at 0.05, 0.01 and 0.001, respectively. ND=Not detected, NS=Not significant, n=Sample size, values within the parenthesis are sample sizes.

(DZ-Dry Zone, IZ-Intermediate Zone, WZ-Wet Zone, DL- Dry zone Low country, WL- Wet zone Low country, WM- Wet zone Mid country, IL- Intermediate zone Low country, IM- Intermediate zone Mid country, IU- Intermediate zone Upcountry).

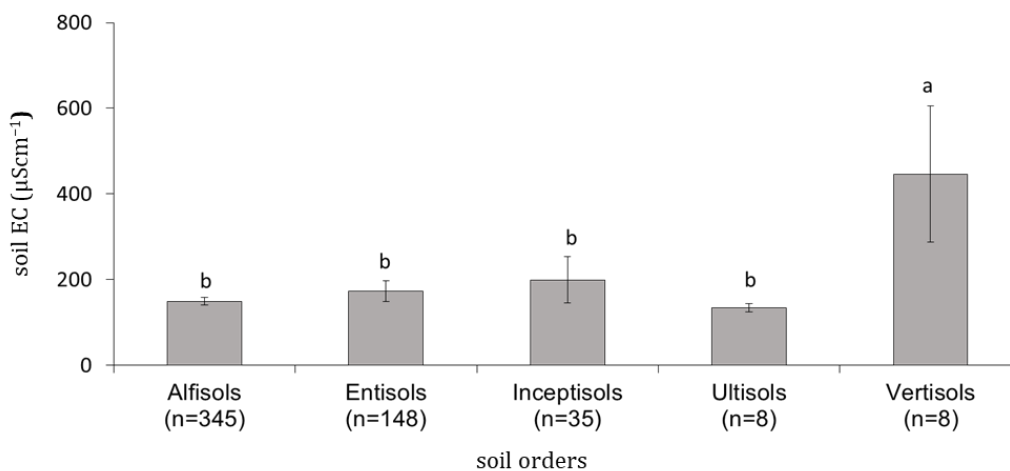


Figure 3. Variability in soil EC as affected by soil orders in Dry zone Low country. Vertical lines represent the standard error (S.E) of the means. Bars followed by the same letter are not significantly different at $P=0.05$. n=sample size.

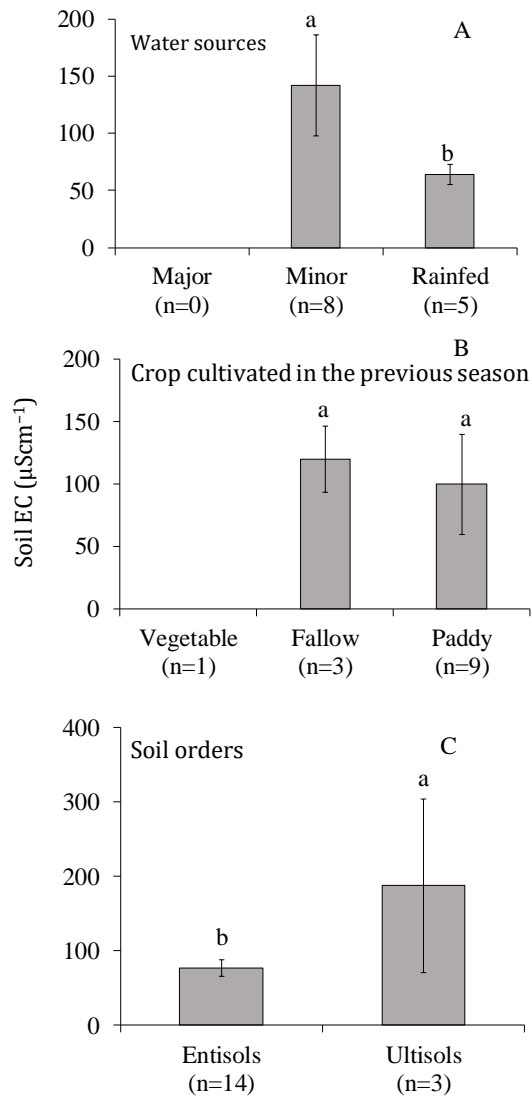


Figure 4. Variation of soil EC values among different water sources (minor irrigation scheme and rainfed), cropping systems adopted (paddy-vegetable; paddy-fallow; paddy-paddy) and soil orders in Wet zone Mid country (WM). Vertical lines represent the standard error (S.E) of the means. Bars followed by the same letter are not significantly different at P=0.05. n=sample size.

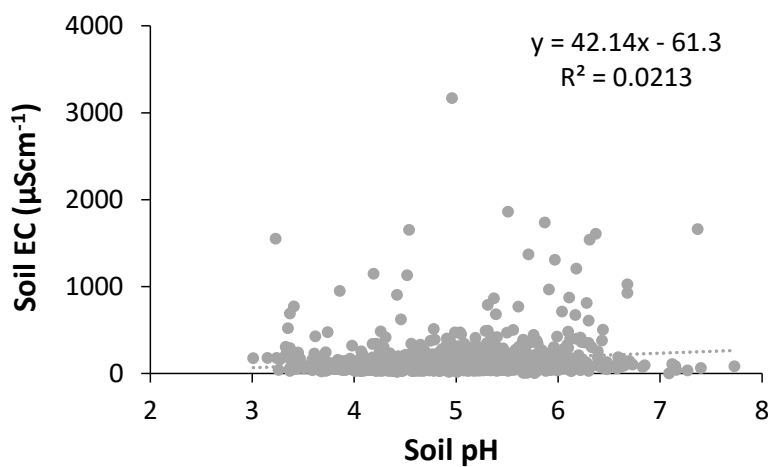


Figure 5. Linear relationship between soil reaction (pH) and electrical conductivity (EC) of soil samples collected across different water sources, cropping systems adopted and soil orders used for rice cultivation (n=998).

Table 4. Correlations (*r*) between pH and EC of soil samples collected from different climatic zones (CZs), Agro-climatic zones (ACZs), water sources used, soil orders and previously cultivated crops

Factors	Classes	n	<i>r</i>	P Value	Equation
Climatic Zone	Dry Zone (DZ)	563	0.1885	<0.0001	EC=59.53pH-131.7
	Intermediate Zone (IZ)	279	-0.0034	0.9550	
	Wet Zone (WZ)	156	0.2517	0.0015	EC=45.23pH-131.7
Agro-Climatic Zone	Low country Dry zone (DL)	563	0.1885	<0.0001	EC=61.46pH-155.8
	Low country Intermediate zone (IL)	247	0.0056	0.9297	
	Mid country Intermediate zone (IM)	17	-0.0128	0.9611	
	zone Up country Intermediate (IU)	15	-0.1954	0.4852	
	Low country Wet zone (WL)	135	0.2928	0.0006	EC=74.77pH-189.7
	Mid country Wet zone (WM)	21	0.1138	0.6234	
	Water source used	Major irrigation	332	0.0649	0.2385
	Minor irrigation	258	0.0913	0.1443	
	Rainfed	203	0.3517	<0.0001	EC=103.49pH-334.9
Soil Order	Vertisols	8	0.8524	0.0072	EC=1198.71pH-6317.4
	Inceptisols	36	-0.2975	0.078	EC=-134.26pH+918.3
	Ultisols	240	0.1936	0.0026	EC= 28.69pH-23.6
	Histosols	4	0.4111	0.5889	
	Entisols	241	0.1997	0.0018	EC=73.89pH-189.9
	Alfisols	430	0.1356	0.0048	EC=40.32pH-60.3
Previous Crop	Rice	374	0.1587	0.0021	EC=33.58pH-32.7
	Fallow	188	0.1976	0.0066	EC=57.85pH-123.4
	OFC	26	-0.1039	0.6134	
	Vegetable	34	-0.1290	0.4672	

Note: equation is provided only for the significant correlations at $P < 0.05$

CONCLUSIONS

Soil pH differed among CZs. Out of the six ACZs studied, DL, IL and IU recorded higher pH values than those of WL, WM and IM. Soil pH in WL, IM and IU was not significantly affected by the water sources used, the cropping system adopted and soil orders. Most of the tested soil samples were not in the optimum range of soil pH for rice cultivation. Soil EC was similar among CZs. When comparing ACZ, the highest soil EC was recorded in IU. Soil EC of WL, IL, IM and IU were not affected by the water sources used, cropping systems adopted or soil orders. In DL, soil EC differed among soil orders. Over, 95% of the tested soil samples were non-saline. Overall results of the current study revealed that most of the rice growing soils in Sri Lanka are not in the optimum range of pH for rice production. However, EC was not beyond the threshold level for rice cultivation. To improve pH and

EC in rice growing soils, it is important to implement site-specific agronomic management practices, considering the variability of pH and EC in micro (e.g. track level) and macro (ACZ level) scales. This includes liming, tailored water management, the incorporation of inorganic fertilizers and organic matter.

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Fig. S1. Map of soil sampling locations

