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Research Article

Distribution of Exchangeable Magnesium in Lowland Rice-Cultivated Soils of Sri Lanka as Affected by the Differences in Climate, Soil, and Water Source

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Abstract

Magnesium (Mg) is an essential macronutrient for plants. Even though Sri Lankans consume rice as the staple food, the Mg status in Sri Lankan paddy soils as affected by its climate, soils, and water sources used are not well understood. This study was conducted to (i) determine the distribution of exchangeable Mg (ex-Mg) concentration, and (ii) examine the interactive effects of agro-climatic zones (ACZs), soil order, and water source in determining the ex-Mg concentration in lowland paddy fields of Sri Lanka. A total of 9,038 soil samples representing six ACZs, six soil orders, and three water sources were collected using a stratified random sampling approach. The ex-Mg concentration was determined after extracting in 0.01 M $CaCl_2$ and detected using inductively coupled plasma-mass spectrometry. The range of ex-Mg was within 0.01-1,610 mg kg^{-1}, with a mean of 210.4 mg kg^{-1}. From the tested soil samples, 66% were Mg-deficient (<240 mg kg^{-1}), 32% were Mg-optimal (240-730 mg kg^{-1}) and 2% were Mg-excessive (>730 mg kg^{-1}). Among the ACZ, the Dry zone Low country had the highest ex-Mg concentration ($p<0.05$). Among the soil orders tested, Vertisols had the highest and Histosols had the lowest ex-Mg concentration ($p<0.05$). Irrigated rice fields had higher ex-Mg than the rainfed systems ($p<0.05$). Soil ex-Mg concentration was positively correlated with soil pH ($p<0.05$) and crop productivity ($p<0.05$). As most rice-growing soils of Sri Lanka are Mg-deficient, it is important to implement strategies specific to ACZs, soil orders, and water sources to improve the soil-Mg status.

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Introduction

Magnesium (Mg) is the eighth most abundant element in the earth's crust [1]. However, the amount of Mg present in soil minerals varies. Ferromagnesian minerals are present in significant proportions in soils derived from mafic igneous rocks. Mafic igneous soils bear high amounts of Mg accessible in the absence of heavy weathering and leaching. Granite, sandstone, and most of the shale-derived soils have relatively low total Mg contents [2]. Based on the variations in bioavailability, Mg in soil is usually identified in different forms such as soluble, exchangeable, and structural forms. Soluble Mg is the minority that exists in the soil solution. Exchangeable Mg (ex-Mg) is attached to the cation exchange sites in the soil colloids. Rest of the Mg in soil is trapped inside mineral forms [1–3]. Soluble Mg is readily available for plant uptake. The ex-Mg forms, which are then gradually replaced by the soil reserves, act as a buffer for the Mg that plants receive from the soil solution [3].

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Magnesium is one of the key mineral elements required by plants for biochemical and physiological processes, including the production and degradation of chlorophyll, photosynthesis, carbohydrate allocation, energy metabolism, and ribosome aggregation [4–6]. Magnesium is a critical element for the performance of numerous enzymes, including adenosine triphosphatases (ATPases), RNA polymerases, phosphatases, protein kinases, glutathione synthases, and carboxylases [7–8]. Chloroplast enzymes are strongly influenced by a minute fluctuation in Mg^{2+} levels in the cytosol and the chloroplast [8]. Furthermore, Mg interacts with K to control cell turgor and as an osmotically active ion to balance the cation-anion in cells [7, 9–10]. Around 75% of Mg in leaves is used to make proteins, while between 15-20% of the total Mg is used to make chlorophyll [11].

In contrast to other cations, Mg has a relatively greater hydrated radius, making it easier to leach especially in acidic and sandy soils with limited cation exchange capacity (CEC), leading to Mg insufficiency in plants [12–14], and with growing crops affecting the yield in different cropping systems [15]. Rapid depletion of Mg from soil makes it difficult for a farmer to keep up with the Mg supply to meet the crop demands [16–17]. Moreover, high inorganic fertilizer input and soil acidity, which result in the antagonistic action of other cations (H^+, NH^{4+}, Al^{3+}, and Mn^{2+}) would affect the plant uptake of Mg [18].

The critical leaf Mg concentration for the growth of most crops such as barley, beetroot, maize, potato, rice, sorghum, and wheat varies between 1 and 2 mg g^{-1} of dry weight. Critical leaf Mg concentration for dry matter formation of *Citrus grandis* (L.) Osbeck was 0.9 mg g^{-1} of dry weight indicating a lower limit for woody perennials [19]. Different soil testing services have given variable recommendations for the levels of ex-Mg in soils for successful crop production [20]. For the growth and development of rice, the levels of ex-Mg for Mg-deficient and Mg-excessive are reported as 240 and 730 mg kg^{-1} of soil, respectively [21]. Moreover, soil application of Mg not only increases the grain weight and yield of wheat but also resulted in better absorption of other nutrients by the crop [22]. Despite being considered an essential plant nutrient, most of the fertilizer recommendation programs have not considered supplying Mg. However, Mg is added to some of the agricultural lands in the form of dolomite to overcome soil acidity [23].

Rice is widely cultivated in most Asian countries, including Sri Lanka, under a wide range of crop management and agro-climatic conditions [24–25]. It is reported that 81% of the soils tested (n=32) had Mg concentrations below the optimal range, indicating possible Mg deficiencies in paddy soils [26]. Moreover, rice-tobacco cropping system had significantly higher soil Mg concentration compared to other land uses [27]. The deficiency of Mg in rice directly influences the yield as it reduces the number of spikelet and 1000-grain weight. It may also reduce grain quality by reducing the percentage of milled rice, and protein and starch content in the grain. Additionally, Mg deficiency enhances the deficiencies of K, P, Ca and Fe [21]. Despite the influence of Mg on the nutrition of rice, the availability of Mg in Sri Lankan paddy soils, and the variation of soil ex-Mg as affected by agro-climatology of Sri Lanka have not been studied extensively.

Sri Lanka is divided into three climatic zones (CZs) based on rainfall intensity. Areas receiving mean annual rainfall less than 1750 mm with a relatively dry season from March to August (i.e., Yala season) are identified as dry zone (DZ). The Wet zone (WZ) receives a mean annual rainfall greater than 2500 mm and is distributed throughout the year without a distinct dry season, while the intermediate zone (IZ) has in-between characteristics concerning the amount and distribution of annual rainfall. Based on the rainfall and elevation, Sri Lanka is divided into seven agro-climatic zones (ACZs). Areas located in altitudes less than 300 m, 300–900 m, and more than 900 m above sea level are called low, mid, and up country regions, respectively. Therefore, the seven ACZs are dry zone low country (DL), intermediate zone low country (IL), intermediate zone mid country (IM), intermediate zone up country (IU), wet zone low country (WL), wet zone mid country (WM) and wet zone up country (WU). Out of those, rice is widely cultivated in all the ACZs except WU due to topographical limitations.

Rice cultivation in DL and IL of Sri Lanka largely depends on the well-distributed cascade irrigation network developed due to the uneven annual rainfall distribution. However, rice cultivation in other regions largely depends on rainfall and supplementary irrigation. Depending on the size of the command area, the irrigation schemes are categorized as major (>80 ha command area) or minor (<80 ha command area) [28]. Moreover, DL and IL in Sri Lanka are warmer and receive higher solar radiation indicating higher yield potential than other ACZs [29]. Soils used to cultivate rice in Sri Lanka consist of different geological origins such as Alfisols, Entisols, Histosols, Inceptisols, Ultisols, and Vertisols [30]. The rice crop productivity in Sri Lanka could also vary among CZs, ACZs, soils, and water availability [29]. The existing variability of climate, soil orders, and water availability in different regions of Sri Lanka may have interactively influenced the ex-Mg concentration in lowland rice fields in Sri Lanka, which is still to be explored. Therefore, the objectives of this study were to

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(i) determine the distribution of ex-Mg concentration, and (ii) examine the interactive effects of ACZ, soil order, and water source in determining the concentration of ex-Mg in lowland paddy fields in Sri Lanka.

Materials and methods

1) Soil sample collection

A total of 9,038 soil samples representing six agro-climatic zones, six soil orders and three water sources were collected using a stratified random sampling approach (Supplementary Material (SM) 1–2). The selection of sampling locations and the collection of soil samples were completed following the approach described in Kadupitiya et al. [31]). In brief, Sri Lanka was divided into 1 km^2 grids using vector operations in QGIS free software (version 3.16.0-Hannover, https://qgis.org). A unique identification number was assigned to each grid by combining latitude and longitude km distance unit (using projected coordinate system EPSG: 5234 Kandawala/Sri Lanka Grid). The whole country was divided into 65,610 grids. After overlaying with the rice land map (1:50000, survey department) a total of 35,537 grids contained rice-cultivated lands. Out of 35,537 grids, 9,038 grids with rice lands were selected for this study using a stratified random sampling approach, based on the administrative districts. The sample collection was done with a smartphone-based location tracking approach which was facilitated by the Google Map as the base map for convenient location tracking [31]. Samples were collected during October-November 2019. Grid ID, ACZ, district, divisional secretariat division (DSD), and the village name of each grid were recorded for each sample during sample collection. From each village, one rice track (i.e., a geographically confined lowland area usually owned and managed by a group of farmers) was selected randomly for sample collection. One sample was taken by combining six subsamples collected from the top 0-15 cm depth from a paddy track to overcome the field-level heterogeneities. Soil samples were air-dried, debris was removed, homogenized, and sieved using a 2 mm sieve. The CZ, ACZ, soil order, and water source used for rice cultivation relevant to each sampling location were extracted by overlaying relevant GIS map layers in QGIS software. Rice yield realized during the immediate previous cropping season (t ha^{-1}) was also collected from the farmers during soil sample collection.

2) Laboratory analysis

The ex-Mg concentration was determined after extracting soil using 0.01 M $CaCl_2$ solution [32–34]. The extraction was made with a soil/solution ratio of 1:10 (w/v) i.e., 5 g soil was dissolved in 50 mL of 0.01 M $CaCl_2$. Samples were shaken for 2 h on an orbital shaker at 200 rpm, and then the solution was centrifuged at 3,600 rpm for four minutes. The supernatant was filtered through a 0.45 μm cellulose acetate syringe filter and the ex-Mg concentration was determined using inductively coupled plasma-mass spectrometry (ICP-MS) (Thermo iCapQ). Forty samples were tested at once in each round. It consisted of 36 soil samples, two laboratory standard soil samples, and two blanks with 0.01 M $CaCl_2$ solution without soil samples for quality control.

For the determination of soil pH, 10 g of soil was measured from each sample and mixed with 50 mL of distilled water. Samples were shaken for two hours in an orbital shaker at room temperature. After resting for 15 minutes, soil pH was measured using a pH meter (Eutech WC PC 650, Singapore). For internal quality control, two laboratory standard soil samples and two blanks only with distilled water were used in each batch (i.e., 36 samples). Moreover, the pH electrode was calibrated daily using the manufacturer's standards (Eutech WC PC 650, Singapore).

3) Preparation of spatial maps

Since each sampling point was tagged with a unique Grid-ID, which was coded with distance (km) coordinate X-Y, the same ID was maintained from field data collection to laboratory analysis and data analysis. This procedure allowed a convenient spatial reference for data set development and facilitated user-friendly GIS map production.

4) Statistical analysis

Descriptive statistics of ex-Mg concentrations were obtained. The ex-Mg concentration was tested for normality using the Shapiro-Wilk test, and all statistical analyses were performed based on the normal distribution after the square root transformation (Figure 1). Analysis of Variance (ANOVA) was performed as a two-step process. First, the difference in ex-Mg concentration of soil samples among ACZ, soil order, water source, and their interactions was determined using the general linear model procedure. As most of the higher-order interactions of ACZ, soil order, and water source were significant, in the second step, differences in ex-Mg concentration of soil samples among soil orders and water sources were tested within each ACZ using ANOVA. The means were compared using Duncan's New Multiple Range Test (DNMRT). Statistical significances were expressed at α=0.05. Statistical analyses were performed using SAS 9.1 software.

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Results and discussion

1) Distribution of exchangeable Mg in rice-cultivated soils and its relationship with crop productivity

Exchangeable Mg concentration was in the range of 0.01–1,610 mg kg^{-1} with mean and median values of 210.4 and 160.4 mg kg^{-1}, respectively (Figure 1). It was evident that 66% of the tested soil samples had ex-Mg concentration less than 240 mg kg^{-1} (i.e., critical value for Mg-deficiency) and only 2% had Mg values greater than 730 mg kg^{-1} (i.e., critical value for excess Mg). Study conducted in 2010, also reported that out of the 32 representative soil samples collected from the three climatic zones of Sri Lanka, 26 soil samples (81%) have shown Mg deficiency [26]. These results indicate the prevalence of Mg deficiency in Sri Lankan rice fields for a long period. The distribution was right-skewed due to the presence of most of the soil samples with low Mg concentrations while a small fraction of soil samples - root transformed Mg concentrations were the best approximation to reach normality.

There was a significant positive correlation ($p<0.05$) between soil ex-Mg concentration and pH (Figure 2). This was largely due to the increased soil ex-Mg concentration in a broad soil pH ranging from 3.5 to 8. The highest soil ex-Mg concentration was observed in a soil pH of 5.5–6.5. Moreover, rice crop productivity also had a significant positive correlation ($p<0.05$) with soil ex-Mg concentration (Figure 2).

Magnesium deficiency in rice would reduce the number of spikelets and grain weight, resulting in a considerable yield loss [21]. Declined crop productivity evidenced in this study along with the reduction in soil ex-Mg concentration could be due to the Mg deficiency (Figure 2). Magnesium deficiency may also lower the grain quality by affecting protein and starch content [21]. Therefore, Mg deficiency interferes with multiple physiological and biochemical processes and affects both the quality and quantity of rice grains produced.

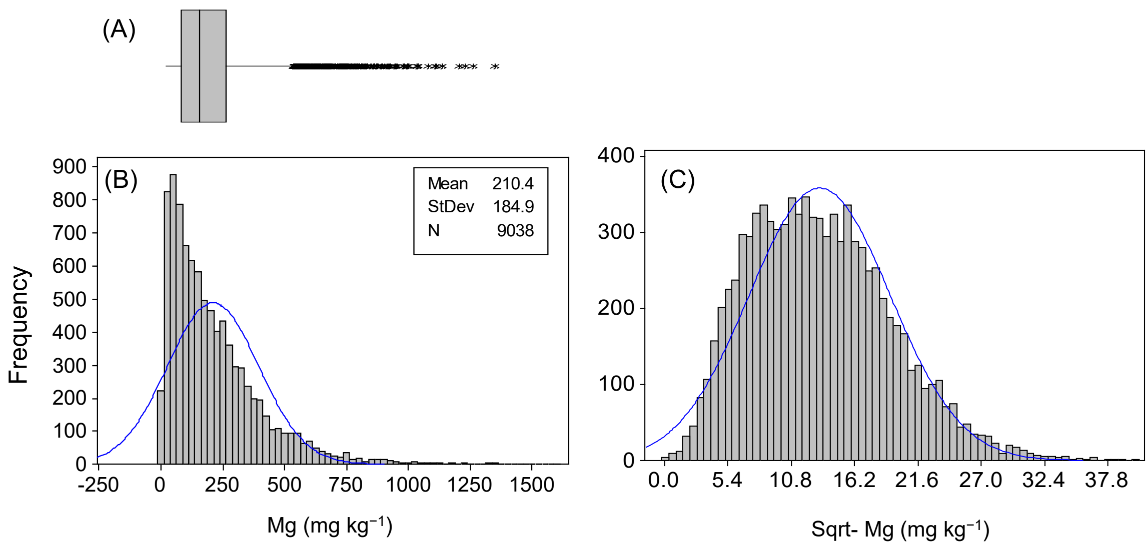

Figure 1 Graphs showing (A) box plot, (B) histogram and (c) square root transformed values of exchangeable magnesium (Mg) concentration of paddy soil samples collected from Sri Lanka.

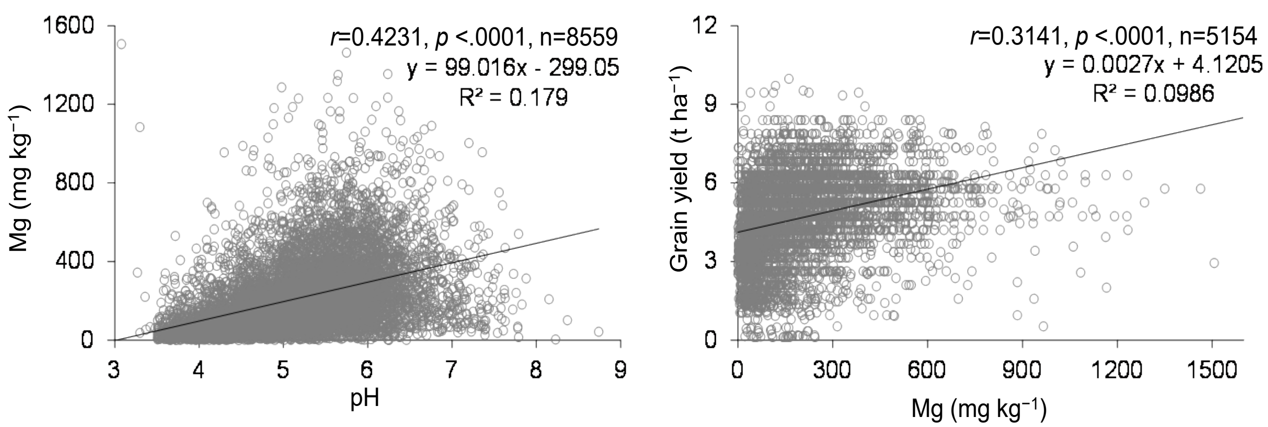

Figure 2 Relationships between soil exchangeable magnesium (Mg) concentration and pH of lowland paddy cultivated soils and the rice crop productivity of Sri Lanka.

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2) Effects of climate on the distribution of exchangeable Mg in rice-cultivated soil

Among the climatic zones, the ex-Mg concentration in DZ was the highest and that in WZ was the lowest (Figure 3(A)). Comparison among ACZs showed that the ex-Mg concentration in DL and IL was higher than that in IM, IU, and WM ($p<0.05$), and that in WL was the lowest ($p<0.05$) (Figure 3(B)). The DL consists of approximately 2/3 of the land area in Sri Lanka (SM 3). Within the DL, there was large spatial heterogeneity in the distribution of ex-Mg, e.g., large areas of northern and southern regions of DL had higher soil ex-Mg concentration while the eastern region of DL had low soil ex-Mg concentration (SM 3). Moreover, most of the paddy fields in the WL had lower soil ex-Mg concentration.

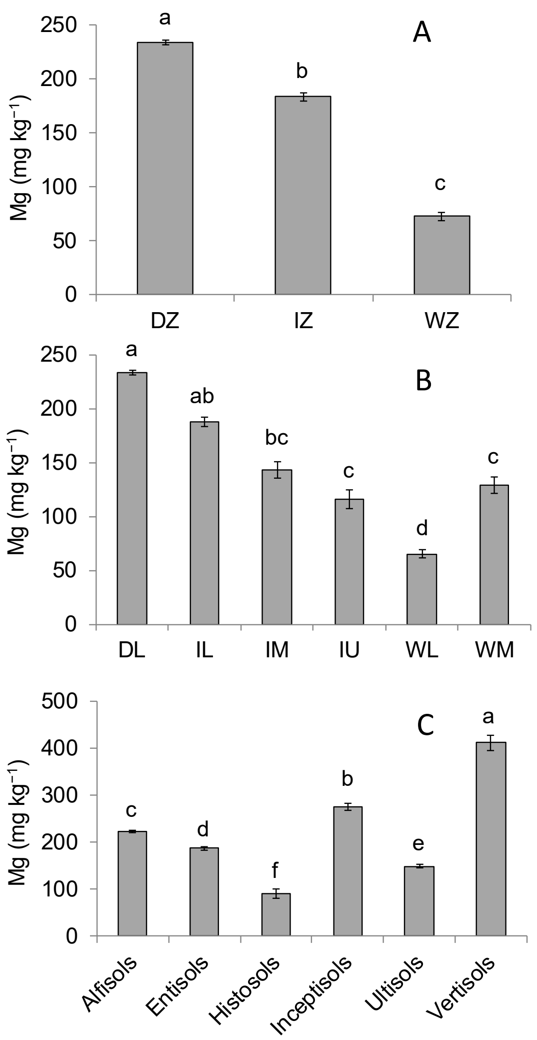

Figure 3 Graphs showing the concentration (mean±S.E.) of exchangeable Mg in the paddy fields used to cultivate rice in (A) different climatic zones and (B) different agro-climatic zones, and (C) different soil orders (C) of Sri Lanka.

The WL of Sri Lanka is characterized by higher annual rainfall than other ACZs [35]. As a result, most of the ex-Mg present in WL soils is subjected to leaching [36–37]. Moreover, Mg deficiency is widely found in acidic soils as Mg is considered to be an alkaline metal [2, 38]. The positive relationship between the soil pH and ex-Mg concentration observed in this study also provides evidence for this (Figure 2). Heavy leaching of basic cations from WL soils makes the WL soils more acidic than that observed in other ACZs of Sri Lanka [39]. All these interactive conditions have caused WL soils to retain the lowest concentration of ex-Mg (Figure 3B). In contrast DL receives the lowest annual rainfall, and least leaching of basic cations and thus shows the highest pH and ex-Mg concentration (Figure 3B). Similar results were reported earlier with a median ex-Mg concentration of 916 mg kg^{-1} in the DL and 149 mg kg^{-1} in the WL of Sri Lanka [39].

3) Effects of soil on the distribution of exchangeable Mg in rice-cultivated soils

Soil ex-Mg concentration varied widely among the soil orders (Figure 3(C)). The six soil orders showed significant differences ($p<0.05$) in their soil ex-Mg concentration in which Vertisols reported the highest soil ex-Mg concentration while that in Histosols was the lowest ($p<0.05$) (Figure 3(C)).

There was a significant interaction between ACZs and soil orders concerning the ex-Mg concentration in soil ($p<0.05$). Both DL and IL had five soil orders, IM and WL had four soil orders each, and IU and WM had three and two soil orders, respectively (Figure 4 and SM 4). Entisoils and Ultisols were observed in all ACZs while Vertisols were found only in a localized region in the DL (Figure 4 and SM 4). Moreover, Alfisols were found in four out of the five ACZs. In DL, Vertisols had a higher soil ex-Mg concentration than Inceptisols ($p<0.05$) (Figure 4). The lowest ex-Mg concentration was recorded in Alfisols, Ultisols, and Entisols ($p<0.05$) (Figure 4). Entisols was largely found in the low-lying flat terrain as localized patches close to the coastal regions of the DL while Alfisols was the major soil type found in the DL (SM 4). In IL, Entisols and Ultisols had higher ex-Mg concentration while that in Alfisols, Inceptisols and Histosols were lower ($p<0.05$) (Figure 4). The two dominant soil orders in IL were Ultisols and Alfisols (SM 4). In IM, Alfisols had higher ex-Mg concentration while that in Inceptisols and Ultisols was lower ($p<0.05$) (Figure 4). In IU and WL, soil ex-Mg concentration between the soil orders was similar ($p<0.05$) (Figure 4). Moreover, Ultisols and Entisols were the dominant soil orders found in WL (SM 4). In WM, Entisols had higher ex-Mg concentration than that in Ultisols ($p<0.05$) (Figure 4).

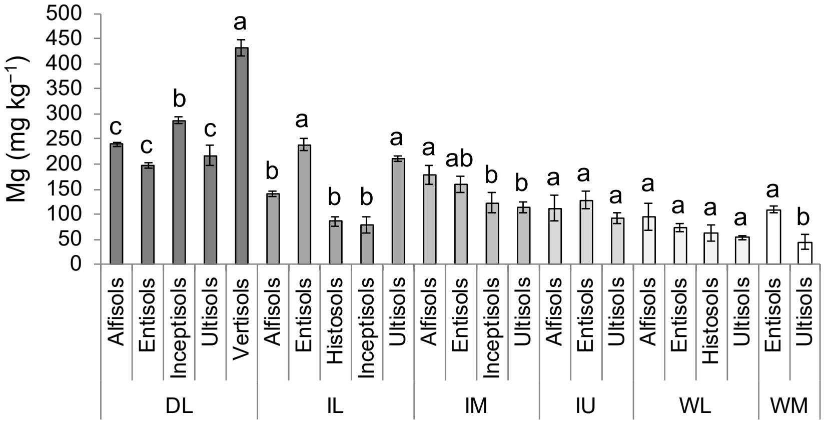

Figure 4 The concentration of exchangeable Mg (mean±S.E.) in the paddy fields used to cultivate rice in different soil orders and agro-climatic zones of Sri Lanka. Different letters over the bars, within each ACZ, indicate statistically significant differences at $p<0.05$.

Vertisols are a group of heavy-textured soils which occur extensively in warm temperatures [40]. This soil type is found only in a localized patch in the DL of Sri Lanka (SM 4) which has the highest temperatures when compared to IL and WL [35]. Vertisols contained the highest available ex-Mg concentrations (Figure 3(C) and 4) representing the majority of ex-Mg in DL. The Vertisols occurring in India, Australia, Sudan, Ethiopia, and other parts of Africa generally have soil pH ranging between 7.5–8.5 in the soil profile which is similar to that of Vertisols in Sri Lanka [40]. High pH favors the retention of ex-Mg in Vertisols. Because of the usual dominance of 2:1 type clay mineral in the 2 μm particle size fraction, Vertisols are also characterized by higher CEC. Since calcium-rich montmorillonite is the major component of Vertisols the highest fraction of CEC is occupied by Ca followed by Mg [40–41]. Furthermore, the high water-holding capacity of Vertisols reduces nutrient leaching with water increasing the ex-Mg [40]. All these favorable characteristics have caused Vertisols to retain more ex-Mg than in other soil orders.

4) Effects of water source on the distribution of exchangeable Mg in rice-cultivated soils

The ex-Mg concentration in soil showed a significant interaction between ACZ and the water source ($p<0.05$). Among the paddy-growing ACZs, major and minor irrigation schemes provided irrigation water for rice cultivation in four ACZs, while rainfed paddy fields were observed in all six ACZs (Figure 5). In DL and IL, paddy fields receiving water from both major and minor irrigation schemes had higher soil ex-Mg concentration than the paddy fields receiving water only from rainfall ($p<0.05$). In IM, paddy fields receiving water from major irrigation schemes had higher soil ex-Mg concentrations than that in minor irrigation schemes ($p<0.05$) (Figure 5). This would be due to the protracted submerged conditions prevailing in irrigated paddy fields and contamination of irrigation water with Mg. The diffusion of Mg is more in irrigated paddy fields when compared to that of rainfed lowlands or uplands as the redox reactions in soil tend to aggravate under submerged conditions [21]. Further, if the paddy fields are irrigated with water contaminated with Mg containing agricultural inputs such as pesticides and fertilizers for a continuous period, the ex-Mg concentration of the irrigated soils would increase [39, 42]. Moreover, nutrient concentrations of the irrigation tanks in IZ and DZ were enriched due to the drier climate, higher evaporation rate, and lower inflow [43]. As a result, the tank cascade system in the IZ of Sri Lanka had a high ex-Mg concentration [43].

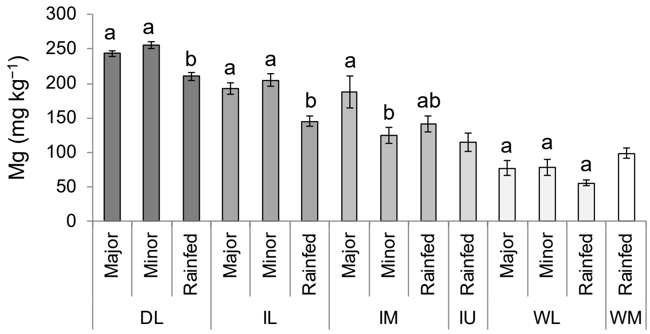

Figure 5 Concentration of exchangeable Mg (mean±S.E.) in the paddy fields used to cultivate rice using different water sources and agro-climatic zones of Sri Lanka. Different letters over the bars, within each ACZ, indicate statistically significant differences at $p<0.05$.

5) Possibilities of improving Mg fertility of rice-cultivated soils

As observed in this study, ex-Mg concentration in IZ and WZ soils of Sri Lanka was below the optimum level. Therefore, it is necessary to improve the soil Mg status of these regions. It can be achieved by crop, water, or/and soil management. Application of either inorganic

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fertilizers containing Mg such as kieserite, dolomite, or magnesite [23, 44–46], or organic fertilizers such as farm yard manure is the most convenient practice to improve soil Mg status [47]. Moreover, chemical composition and granule size of the inorganic fertilizer applied also influence the use efficiency of Mg fertilizer added [37].

Apart from the incorporation of Mg sources, it is important to minimize Mg losses from soil. Minimizing the percolation by compacting subsoil during land preparation would help to control the leaching of Mg and other nutrients from the soil [48]. The WZ of Sri Lanka is characterized by slopy lands [35]. Therefore, it is important to adopt soil conservation practices such as establishing cover crops, conservation tillage or no till agriculture, contour farming and terracing to minimize the soil erosion and runoff from these lands. It will minimize the Mg runoff from slopy lands.

In all the ACZs, it is important to estimate the Mg removed through crop harvest and implement balance fertilizer application schedules. Otherwise, the excess application can result in toxicities whereas the reduced application would cause harvest loss. Either of these would directly affect the economic condition of the Sri Lankan farmers. Application of Mg fertilizer to soil has a decreasing impact on plant uptake of toxic trace elements such as cadmium [49–50]. The treatment of Ca-Mg phosphate fertilizer coupled with continuous flooding has reduced the available content of cadmium in soils resulting in a reduction in Cd accumulation in rice grains [51]. However, excessive liming of rice fields with Mg minerals without initial soil pH analysis would also increase Mg content in soil inhibiting the absorption of other essential minerals such as Zn [52]. Therefore, it is important to conduct a proper soil analysis before the application of any form of Mg fertilizer into the soil.

Breeding Mg-tolerant rice varieties is another possible approach to manage Mg nutrition in rice. The possibility of utilizing the Mg transporter gene named *OsMGT1* for molecular breeding of low-Mg tolerant plants in the future is also reported [53]. Moreover, the same gene can be utilized in breeding salt-tolerant rice varieties [54–55], and thus giving multiple tolerance. Therefore, breeding such varieties would increase the arable land area without additional cost for land management. Moreover, the reduced fertilizer application would have a positive environmental impact. Finally, by increasing crop yields and improving grain quality, Mg tolerant rice varieties can help to increase food security.

Conclusion

Exchangeable soil-Mg concentration in lowland rice-cultivated soils in Sri Lanka varied depending on the CZ, ACZ, soil orders, water sources used, and their interactions. Moreover, exchangeable soil-Mg concentration had a significant positive correlation with soil pH. There was a spatial heterogeneity of soil Mg distribution, e.g., higher in DL among ACZs, and higher in Vertisols among the soil orders tested. Only in DL and IL, the Mg concentration was higher in irrigated paddy fields than that in rainfed fields. The spatial maps generated using a large number of samples could be used to identify the areas with low and high Mg levels in the country and make area-specific agronomic and administrative decisions. As the majority of the Sri Lankan rice soils tested contained low levels of exchangeable Mg, it is important to implement strategies to increase exchangeable Mg in the soil to ensure high productivity in rice crops. Key mitigation strategies include the application of either inorganic and/or organic fertilizers, proper water management, and the breeding of rice varieties that are tolerant to Mg deficiency.

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