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RESEARCH ARTICLE

Exchangeable molybdenum concentration in lowland paddy fields of Sri Lanka as affected by the differences in agro-climatic zones, soil orders, and water sources

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Summary

Molybdenum (Mo) is an essential micronutrient for plants. However, Mo status in Sri Lankan paddy fields as affected by climate and soil is not known. This study was conducted to (i) determine the distribution of exchangeable Mo concentration, and (ii) examine the interactive effects of the agro-climatic zone (ACZ), soil order, water source, and their interactions in determining exchangeable Mo concentration in lowland paddy fields of Sri Lanka. A total of 3,719 soil samples representing six ACZs, six soil orders, and three water sources were collected using a stratified random sampling approach. Exchangeable Mo concentration was determined after extracting in 0.01 M $CaCl_2$ solution and detected using inductively coupled plasma-mass spectrometry. Soil Mo concentration varied in the range of 0.01 to 245 μg kg^{-1} with a mean of 25.9 μg kg^{-1}. Samples collected from the Wet zone, particularly Wet zone Low country, had higher Mo concentrations than those reported in other ACZs. Among the soil orders tested, Histosols had a higher Mo concentration while that in other soil orders was similar. Rainfed paddy fields had more Mo than supplementary irrigated paddy fields. Spatial maps were generated to visualise the geographical variation in soil Mo concentration. Due to the presence of a spatial heterogeneity of exchangeable Mo concentration, it is important to implement ACZ, soil, and water source-based strategies to improve Mo status in Sri Lankan paddy fields.

Keywords: bioavailability; fertility; irrigation; rice; spatial variation

Introduction

Molybdenum (Mo) does not exist naturally in the pure metallic state but occurs in association with other elements in the predominant oxidation states of Mo(IV) and Mo(VI) (Jonmaire, 2015). Parent material, degree of weathering, landscape position, drainage, and soil organic matter content determine the Mo concentration in soil. Highly weathered and leached acidic soils have low Mo concentrations whereas alluvial soils with high water tables on granite parent materials have high Mo (Reddy *et al.*, 1997). Mo is found in four main fractions in soil; dissolved in soil solution, as oxides of aluminium (Al), iron (Fe), and manganese (Mn), in solid phases such as molybdenite (MoS_2), powellite ($CaMoO_4$), ferrimolybdite ($Fe_2(MoO_4)_3$), and wulfenite ($PbMoO_4$), and associated with organic compounds (Reddy *et al.*, 1997).

The majority of Mo can be found in soils and water as molybdate anion, MoO_4^{2-} (Jonmaire, 2015). Acidic soils rich in Fe and Al oxides and hydroxides react with MoO_4^{2-} to form a series of soluble hydroxymolybdates. In addition, acidic soils help MoO_4^{2-} to react with octahedral Al to replace the surface hydroxide (OH) groups (Reddy *et al.*, 1997). Therefore, the adsorption of Mo is highly dependent on soil pH, i.e., as pH decreases, the adsorption of Mo increases. It is reported that the maximum adsorption of Mo occurs at pH 4.0 (Reddy *et al.*, 1997). Above pH 4, MoO_4^{2-} is the common anion followed in decreasing order by $MoO_4^{-} > HMo_4^{-} > H_2Mo_4 > MoO_2(OH)^{+} > MoO_2^{2+}$ (Kaiser *et al.*, 2005).

Solid phases of Mo are dissolved in water to release molybdate anion into the soil solution where plants absorb it. Mo is not particularly physiologically active on its alone. More frequently, it occurs as an essential component of a complex organic pterin known as a Mo co-factor (Moco). Assimilation of nitrate is the most significant involvement of Mo in plant metabolism. Therefore, Mo deficiency is similar to nitrogen (N) deficiency in plants. When a plant is deficient in Mo, leaves begin to wilt, grow slowly, and possibly cause them to wither. These are brought on by necrosis in the tissue and disparity of the vascular bundles at the early stages of leaf development (Rana *et al.*, 2020). Apart from the involvement of Mo in N metabolism, it is required in the synthesis of phytohormones; abscisic acid and indole-3 butyric acid (Kaiser *et al.*, 2005), and present as a pterin-co-factor in the active centre of plant enzymes catalysing key steps of carbon, and sulfur metabolisms (Manuel *et al.*, 2018). The average Mo concentration in the tissues of common crops usually ranges from 0.8 to 5 mg kg^{-1} (Shi *et al.*, 2018). Moreover, Mo toxicity in rice plants was observed when tissue Mo concentration was in the range of 10–50 mg kg^{-1} (Kabata-Pendias and Pendias, 2000), and Mo deficiency was observed when tissue Mo concentration was less than 0.5 mg kg^{-1} (Fageria, 2013). It was also reported that Mo either alleviates or enhances the toxicities of other mineral elements, e.g., increased Mo suppressed the cadmium toxicity in rice by regulating the oxidative stress and antioxidant gene expression (Imran *et al.*, 2020).

Despite the influence of Mo on the nutrition of rice plants and humans, the availability of Mo in Sri Lankan rice-cultivated soils, and the variation of soil Mo as affected by agro-climatology are not yet explored. Areas receiving mean annual rainfall <1,750 mm with a relatively dry season from March to August (*i.e. Yala* season) are identified as Dry zones. The Wet zone receives a mean annual rainfall greater than 2,500 mm and is distributed throughout the year without a distinct dry season while the Intermediate zone has in-between characteristics concerning the amount and distribution of annual rainfall. When considering elevation, areas located less than 300 m, 300–900 m, and more than 900 m above sea level are called Low, Mid, and Up Country regions, respectively. Based on the rainfall and elevation, Sri Lanka is divided into seven ACZs. 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. Depending on the size of the command area, irrigation schemes are categorised as major (more than 80 ha command area) or minor (less than 80 ha command area) (Imbulana, 2006). When rice is cultivated with the input of irrigation water over a long period of time, there is a possibility of increasing soil Mo concentration due to the continuous accumulation of impurities including Mo, and continuous leaching in rainfed paddy fields would deplete exchangeable Mo. However, this has not been tested. Moreover, DL and IL in Sri Lanka are warmer and receive higher solar radiation indicating higher yield potential than other ACZs (DOA, 2020; Kadupitiya *et al.*, 2022; Suriyagoda, 2022). Soils used to cultivate rice in Sri Lanka have different geological origins such as Alfisols, Entisols, Histosols, Inceptisols, Ultisols, and Vertisols (Panabokke, 1978). These soils differ in their characteristics such as the

Table 1. The number of soil samples collected from each agro-climatic zone (ACZ), soil order, and water source to test exchangeable molybdenum concentration in paddy soils

	ACZ						
	Dry Zone Low country	Intermediate Zone Low country	Intermediate Zone Mid country	Intermediate Zone Up country	Wet Zone Low country	Wet Zone Mid country	Total
Soil orders							
Alfisols	1,397	138	4	1	2	–	1,542
Entisols	891	90	12	5	177	17	1,192
Histosols	–	14	–	–	19	–	33
Inceptisols	261	7	4	–	–	–	272
Ultisols	22	280	15	2	225	3	547
Vertisols	133	–	–	–	–	–	133
Water sources							
Major	1,247	206	1	–	40	–	1,494
Minor	658	199	9	–	72	–	938
Rainfed	799	124	25	8	311	20	1,287
Total	*2,704*	*529*	*35*	*8*	*423*	*20*	*3,719*

degree of weathering (i.e. weathering stage), soil pH, organic matter content, and mineral composition (Dassanayake *et al.*, 2020; Indraratne 2020). It has also been found that the rice crop productivity in Sri Lanka varies among ACZs, soil orders, and water sources (DOA, 2020). The variability of ACZ, soil, and water source in different regions of Sri Lanka may have interactively influenced the exchangeable Mo concentration in lowland paddy fields. Therefore, the objectives of this study were to (i) determine the distribution of exchangeable Mo concentration, and (ii) examine the interactive effects of ACZ, soil order, and water source on determining the concentration of exchangeable Mo in lowland paddy fields in Sri Lanka.

Methodology

Soil sample collection

A total of 3,719 soil samples representing six agro-climatic zones and six soil orders were collected using a stratified random sampling approach (Table 1, Figure 1). Selection of sampling locations and collection of soil samples were completed following the approach described in Kadupitiya *et al.* (2021). In brief, Sri Lanka was divided into 1 km^2 grid using vector operations in Quantum Geographic Information System (QGIS) free software (version 3.16.0-Hannover, https://qgis.org). A unique identification number was assigned for 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), 35,537 grids were found to be containing rice-cultivated lands. Out of 35,537 grids containing rice lands, 4,816 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 Maps as the base map for convenient location tracking (Kadupitiya *et al.*, 2021). Samples were collected during October–November 2019. Grid ID, ACZ, district, divisional secretariat division, and the village name of each grid were recorded for each sample during sample collection. From each village, one paddy track (i.e., a geographically confined lowland area usually owned and managed by a group of farmers) was selected randomly for the purpose of sample collection. One sample was taken by combining six subsamples collected at 0–15 cm depth from a paddy track to overcome the field-level heterogeneities. Soil samples were air-dried, debris were removed, homogenised, and sieved using a 2 mm sieve. The CZ, ACZ, soil order, and water sources used for

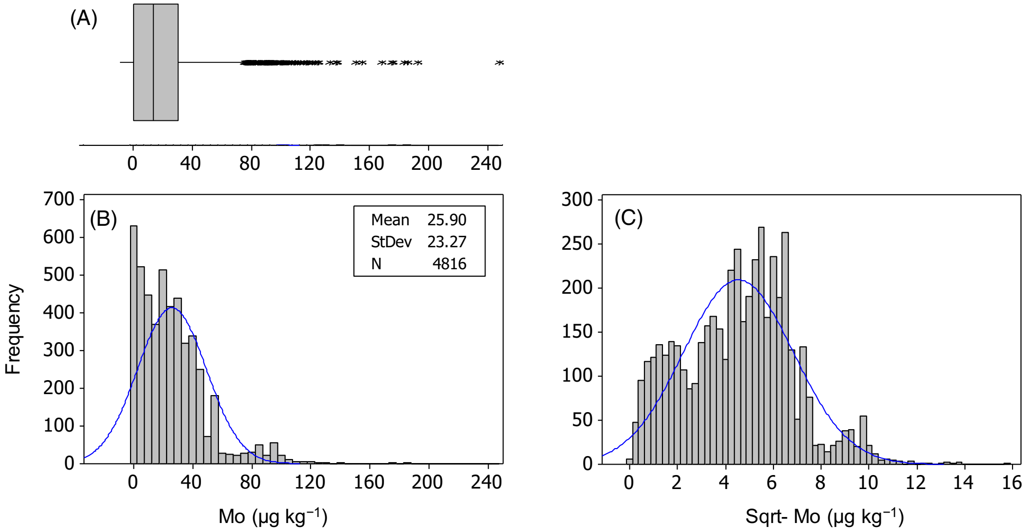

Figure 1. Box plot (A), histogram (B), and square root-transformed values (C) of Mo concentration of paddy soil samples collected from Sri Lanka. In the box plot, box represents the central 50% of the data and outer lines represent the remaining 50% of the data. Moreover, dots on the right side represent the location of outliers.

rice cultivation relevant to each sampling location were extracted by overlaying relevant GIS map layers in QGIS software.

Laboratory analysis

Mo was extracted using 0.01 M $CaCl_2$ solution (Houba *et al.*, 2000; van Erp *et al.*, 2001; Zbíral and Němec, 2005). The extraction was made with a soil/solution ratio of 1:10 (w/v) i.e. 5 g soil was dissolved in 50 mL 0.01 M $CaCl_2$ solution. Samples were shaken for 2 hours 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. Mo concentration in the solution 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.

Preparation of Mo 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 easy spatial reference for data set development and facilitated user-friendly GIS map production.

Statistical analysis

Descriptive statistics of Mo concentrations were obtained. Mo 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 Mo concentration of soil samples among ACZ, soil order, water source, and their interactions was determined using the

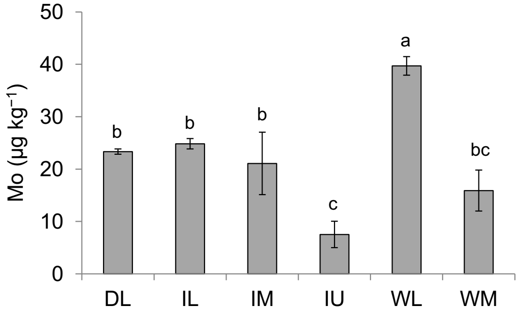

Figure 2. Concentration of molybdenum in the paddy fields used to cultivate rice in different agro-climatic zones of Sri Lanka (mean±S.E). *Note*: DL-Dry zone Low country, IL-Intermediate zone Low country, IM-Intermediate zone Mid country, IU-Intermediate zone Up country, WL-Wet zone Low country, and WM-Wet zone Mid country. Different letters over the bars indicate statistically significant differences at $p < 0.05$.

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 Mo 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. Statistical significances were expressed at $\alpha = 0.05$. Statistical analyses were performed using SAS 9.1 software.

Results

Exchangeable Mo concentration was in the range of 0.01–245 µg kg^{-1} with mean and median concentrations of 25.9 and 21.4 µg kg^{-1}, respectively (Figure 1). The distribution was right skewed due to the presence of a large majority of soil samples with low Mo concentrations while only a small fraction of soil samples with extremely high Mo concentrations. As a result, square root-transformed Mo concentrations were the best approximation to reach normality.

When comparing ACZs, rice-cultivated soils in WL had the highest Mo concentration while that in IU was the lowest ($p < 0.05$) (Figure 2). Concentration of Mo in the other four ACZs was similar ($p > 0.05$) (Figure 2). Despite Sri Lanka being divided into seven ACZs, DL consists of approximately 2/3 of the land area (Figure 3). Within DL, there was large spatial heterogeneity in the distribution of Mo, e.g., most of the rice-cultivated soils in the north-eastern and north-central regions of DL had lower Mo concentrations while the rest of DL had higher Mo concentrations. Moreover, most of the WL regions also had higher Mo concentrations (Figure 3).

When comparing different soil orders, Histosols recorded the highest Mo concentration while that in other soil orders was similar (Figure 4). Alfisols being the major soil order used to cultivate rice in DL contained a lower concentration of Mo, which was similar to Inceptisols, Ultisols, and Vertisols ($p > 0.05$) (Figures 4, 5).

There was a significant interaction between ACZ and soil orders when determining Mo concentration in soil ($p < 0.05$). Both DL and IL had five soil orders, IM and WL had four soil orders, and IU and WM had three and two soil orders, respectively (Figure 6). Entisols and Ultisols were observed in all the ACZs while Vertisols were found only in a much-localised region in the DL (Figure 6). Moreover, Alfisols were found in four out of five ACZs.

In DL, Ultisols had the lowest Mo concentration ($p < 0.05$) while that in other soil orders was similar ($p > 0.05$) (Figure 6). Vertisols were found only in a restricted area located in the low-lying north-western region of Sri Lanka (Figure 5). Entisols were largely found in the low-lying flat terrain as localised patches close to the coastal regions of the DL while Alfisols were the major soil orders found in DL (Figures 3, 5). In IL, Inceptisols had the highest Mo concentration while that in Alfisols, Histosols, and Ultisols was the lowest ($p < 0.05$) (Figure 6). The two dominant soil orders

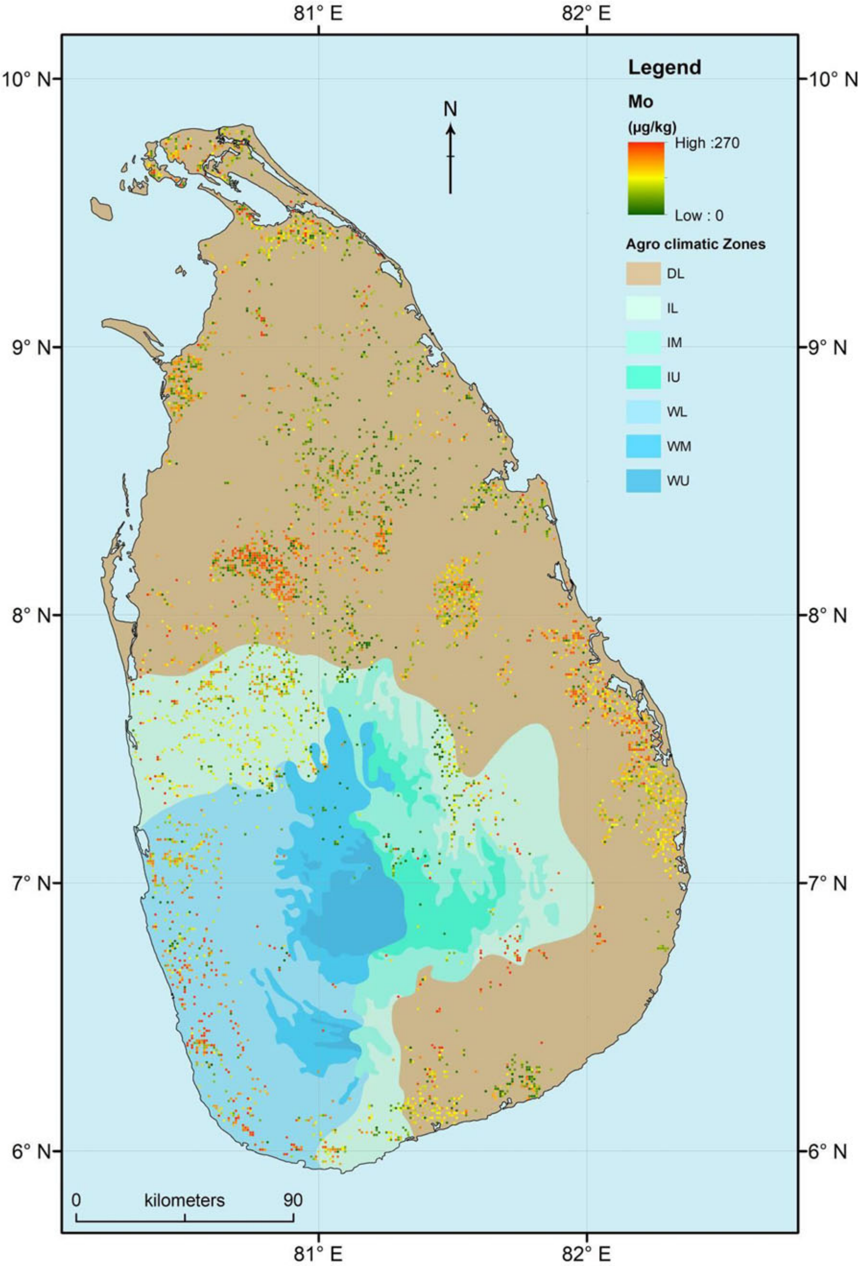

Figure 3. Spatial distribution of molybdenum concentration in the paddy fields used to cultivate rice in different agro-climatic zones of Sri Lanka, *Note*: DL-Dry zone Low country, IL-Intermediate zone Low country, IM-Intermediate zone Mid country, IU-Intermediate zone Up country, WL-Wet zone Low country, WM-Wet zone Mid country, and WU-Wet zone Up country.

found in IL were Ultisols and Alfisols (Figures 3, 5). In IM, Ultisols reported higher Mo concentration than that in Alfisols. In IU and WL, Mo concentrations were similar among the soil orders within each ACZ ($p > 0.05$), whereas in WM, it was higher in Ultisols ($p > 0.05$) (Figure 6). All the soil orders in IU retained very low Mo concentrations than the soils in other ACZs.

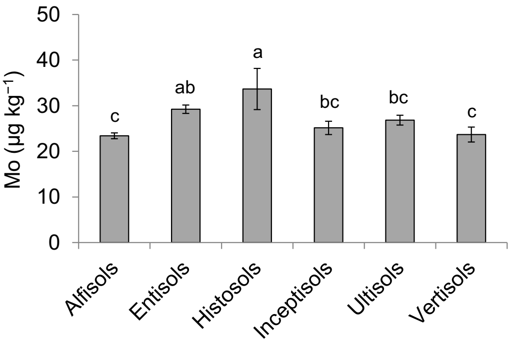

Figure 4. Concentration of molybdenum in the paddy fields used to cultivate rice under different soil orders of Sri Lanka (mean±S.E.). Different letters over the bars indicate statistically significant differences at $p < 0.05$.

When major and minor irrigation schemes provided supplementary water for rice cultivation in four ACZs, rainfed paddy fields were observed in all six ACZs (Figure 7). There was a significant interaction between ACZ and water source when determining exchangeable Mo concentration ($p < 0.05$). When comparing different water management methods, rainfed soils retained more Mo than the paddy fields receiving supplementary irrigation water either from major or minor irrigation schemes in most of the ACZs. Moreover, rainfed paddy fields in IU and WM retained a lower Mo concentration than other rainfed systems (Figure 7).

Discussion

Distribution of Mo in paddy soils

Even though critical plant Mo concentrations causing Mo deficiency and toxicity have been reported in the literature, as far as authors are aware, critical soil exchangeable Mo concentrations causing Mo deficiency and toxicity to rice plants have not been identified. However, only in one instance soil exchangeable Mo concentration of 200–500 µg kg^{-1} was considered the critical Mo level for rice grown in the Indo-Gangetic Plain (Nayyar *et al.*, 2001). The exchangeable soil Mo concentration observed in this study was in the range of 0.01–245 µg kg^{-1}. Accordingly, soil samples tested in this study had Mo concentrations much lower than those reported by Nayyar *et al.* (2001). The mean exchangeable Mo concentration reported in this study was 25.9 µg kg^{-1}, and it was nearly 10 times less than that required for the optimal functioning of rice. Similar soil Mo deficiencies have been reported in other countries as well (Nayyar *et al.*, 2001; Sun and Selim, 2020). Therefore, understanding the existing soil Mo deficiency, and implementation of strategies to improve Mo nutrition in Sri Lankan rice soils are required.

The effects of agro-climatic zone, water source, and soil orders on determining exchangeable Mo concentration in paddy soils

Despite having higher annual rainfall in WZ, particularly WL than other ACZ (AgStat, 2021), WL reported higher exchangeable soil Mo concentration (Figures 2 and 3). It has been reported that Mo leaching from acidic soil is limited due to the low solubility of Mo (Riley *et al.*, 1987). As reported by Fageria (2013), when pH increases from 4.7 to 7.5, water-soluble Mo concentration increases about six-fold due to the replacement of adsorbed Mo by OH^- ions resulting in heavy Mo leaching. Soils in WZ are acidic while the soils in DZ and IZ are neutral to alkaline (Balasooriya *et al.*, 2021). Therefore, the solubility and mobility of Mo in WZ soils were lower leading to higher Mo accumulation while the response in DZ and IZ soils was the opposite. This was further supported by the significant negative correlation between soil pH and exchangeable

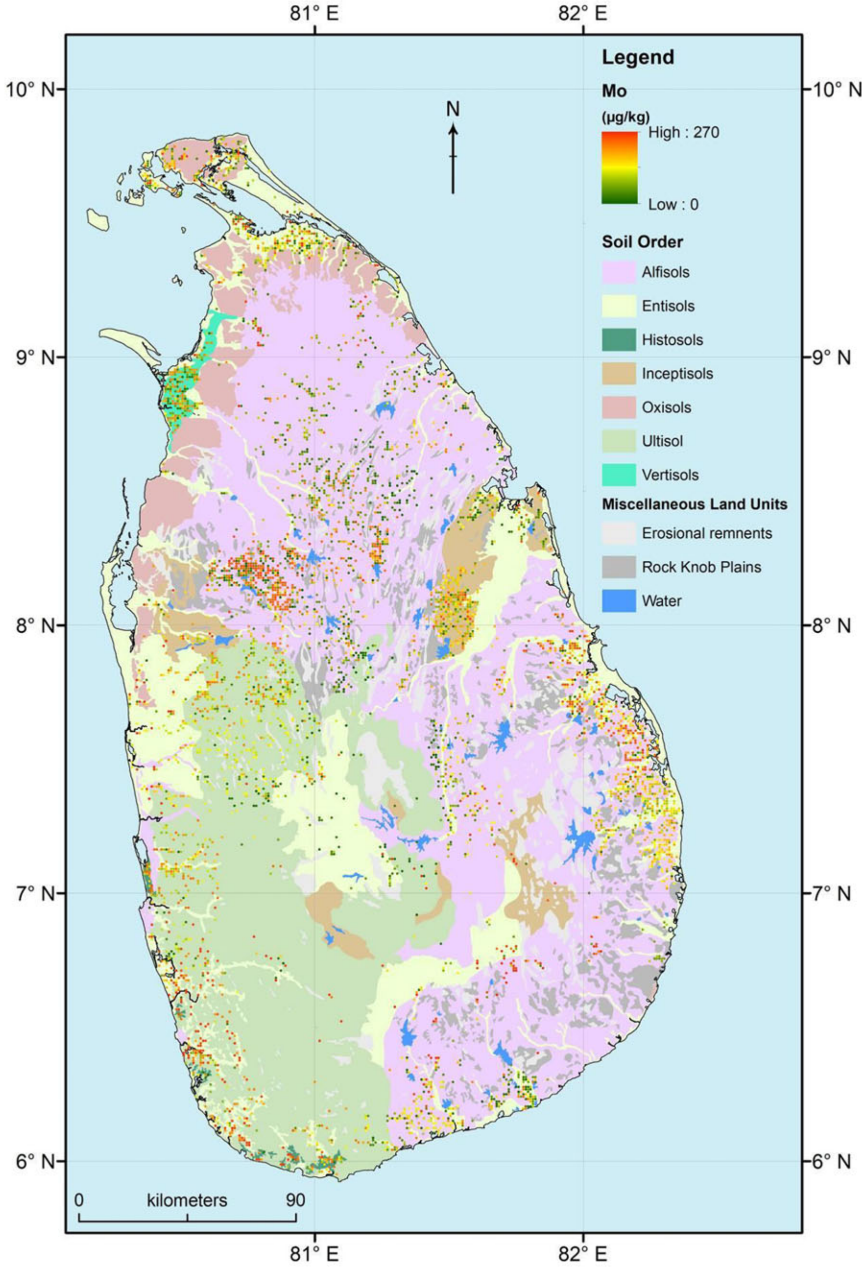

Figure 5. Spatial distribution of molybdenum concentration in the paddy fields used to cultivate rice under different soil orders of Sri Lanka.

Mo concentration in the tested soil samples (data not shown). As a result, soils in WZ reported the highest soil exchangeable Mo concentration while those in DZ and IZ were lower.

The affinity of Fe and Al oxides to Mo is high as those oxides increase Mo sorption in soil (Goldberg *et al.*, 1996; Lang and Kaupenjohann, 2003). Previous studies have explained the anion sorption mechanisms in which Mo, Fe, and Al oxides could form inner-sphere surface complexes through ligand exchange (Ferreiro *et al.*, 1985). Acidic soil pH in WZ soils was reported to retain

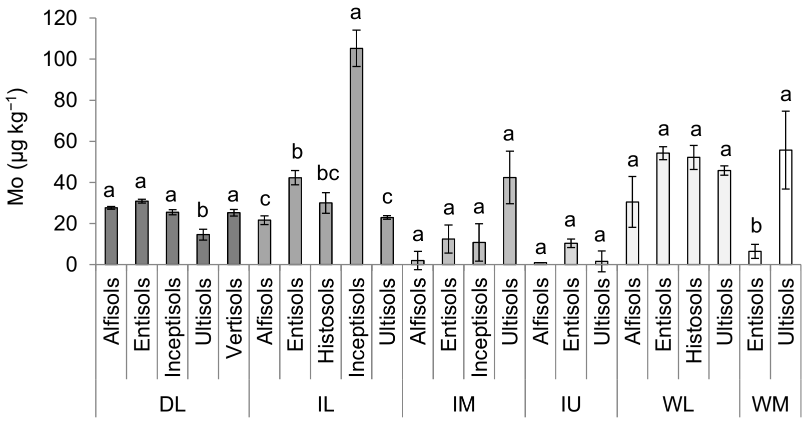

Figure 6. Concentration of molybdenum in the paddy fields used to cultivate rice in different soil orders and agro-climatic zones of Sri Lanka (mean±S.E.). *Note*: DL-Dry zone Low country, IL-Intermediate zone Low country, IM-Intermediate zone Mid country, IU-Intermediate zone Up country, WL-Wet zone Low country, WM-Wet zone Mid country. Different letters over the bars, within each ACZ, indicate statistically significant differences at $p < 0.05$.

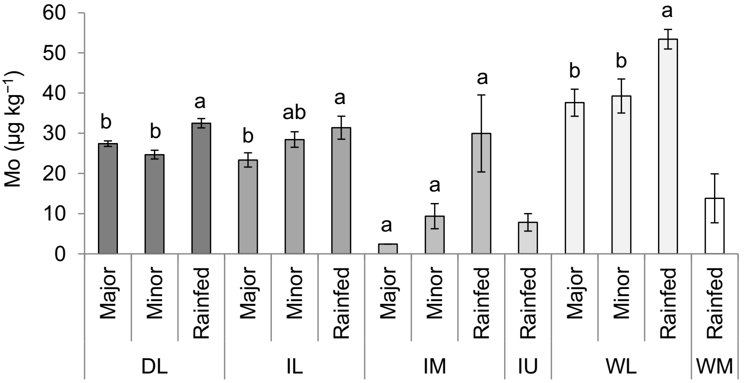

Figure 7. Concentration of molybdenum in the paddy fields used to cultivate rice using different water sources and agro-climatic zones of Sri Lanka (mean±S.E.). *Note*: DL-Dry zone Low country, IL-Intermediate zone Low country, IM-Intermediate zone Mid country, IU-Intermediate zone Up country, WL-Wet zone Low country, and WM-Wet zone Mid country. Different letters over the bars, within each ACZ, indicate statistically significant differences at $p < 0.05$.

higher Fe and Al (Lindsay, 1979), leading to the formation of Fe-Al-Mo complexes in WZ soils than that observed in DZ and IZ soils. In addition to Fe/Al oxide content, soil organic matter and clay minerals are also correlated with the amount of Mo adsorbed. Mo is strongly bound to organic matter, which aids in preventing Mo from leaching (Sun and Selim, 2020), and organically bound Mo is over 40 times larger than Mo bound to Fe and Mn oxides (Marks *et al.*, 2015).

The lowest exchangeable Mo concentration was reported in IU (Figure 2). The DZ and IZ of Sri Lanka experience higher temperatures than that in WZ (AgStat, 2021), which accelerates the decomposition of organic matter. Also, Alfisols found in the IZ contain Ca/Mg-bearing minerals leading to neutral pH (Bockheim and Hartemink, 2017; Indraratne, 2020). Moreover, the hilly topography in the IU region accelerates the heavy leaching of mineral elements (Dassanayake *et al.*, 2020). Therefore, the Mo adsorption capacity of the soils in IU may have been lower resulting in higher Mo leaching.

Histosols are mainly derived from organic parent material and are characterised by organic matter contents higher than 50% (Everett, 1983). Therefore, Histosols can retain more Mo, which leads to less Mo leaching. This is evident from the results displayed in Figure 4. Entisols occur on recent marine calcareous sediments of the flat terrain (Anonymous, 2007). Calcareous soils have high pH, which increases the concentration of liable Mo by reducing sorbed Mo (Marks *et al.*, 2015). However, as the terrains are flat, they do not leach out, instead the exchangeable Mo concentration increases. Inceptisols in the IL show a striking increase in Mo when compared with other soil orders and ACZs (Figure 6). This may be due to the presence of calcareous soil, high pH, and flat terrain resulting in less Mo leaching. In basic calcareous soils, Mo is strongly sorbed onto oxides, clay minerals, or soils by a ligand exchange mechanism and this reaction forms an inner-sphere complex. Sorption of the anion is controlled by pH, density of surface sites, and concentration of the anion. The relative adsorption of the clay minerals increases in the order illite<kaolinite< nontronite<metahalloysite (Sun and Selim, 2020). Among these clay types, nontronite and metahalloysite are not reported in Sri Lankan soils, whereas kaolinite is found abundant all over Sri Lanka (Indraratne, 2020). As the WZ soils have more illite than the IZ and DZ (Indraratne, 2020), the adsorption capacity of the soils of WZ is lesser, increasing its bioavailability.

Irrigated rice fields retain more standing water than rainfed rice soils promoting Mo leaching. This may be the reason for the observed higher soil Mo concentration in rainfed soils than that in irrigated soils within each ACZ.

Possible interventions to improve Mo concentration in paddy soils

As discussed above, rice-cultivated soils in Sri Lanka have lower soil Mo concentration than required for optimal growth. High pH in the WZ would increase the solubility of Mo and then leach out with high rain, reducing the bioavailability of Mo. In contrast, high pH in DZ increases the solubility and bioavailability of Mo due to less leaching. Therefore, liming in WZ and hilly areas would further reduce bioavailable Mo concentration whereas liming in the DZ would increase the bioavailable Mo concentration.

Incorporation of organic matter into soils in rainy and hilly areas would be beneficial as it would increase the adsorption capacity of Mo and minimise leaching. However, the addition of organic matter would be disadvantageous to drier areas as it would decrease bioavailable Mo by reducing its mobility.

The incorporation of Mo fertiliser is another approach to improve Mo nutrition in rice soils. Sodium molybdate, ammonium molybdate, and Mo trioxide are the common sources of Mo (Nayyar *et al.*, 2001). It has also been found that sulfate ions, Cu, Mn, and Zn negatively affect Mo absorption by plants if they are present in excess amounts in the soil solution (Fageria, 2013). This is due to the ability of Mo to act as a reduction catalyst to counteract the oxidising effects of them (Anderson, 1956). In contrast, P ions show a synergistic effect with Mo absorption as they increase the availability of Mo in the soil by exchanging with adsorbed molybdate on the clay (Stout *et al.*, 1951). Therefore, testing of S, Cu, Mn, Zn, and P concentrations in rice soils would be beneficial for a better understanding of the dynamics between those elements and Mo in Sri Lankan lowland paddy soils.

Mo plays a vital role in the accumulation and utilisation of soil N (Sun and Selim, 2020), and the deficiency symptoms of N and Mo in plants are similar (Nayyar *et al.*, 2001). Therefore, Mo-deficient soils may mislead rice growers indicating N deficiency. The excess N fertilisation would lead to N leaching and groundwater contamination aggravating environmental and socio-economic problems (Bouchard *et al.*, 1992; Wang *et al.*, 2019). Proper identification of nutrient deficiency symptoms such as Mo deficiency through soil testing would reduce the unnecessary expenditure on other fertilisers such as N. This would benefit both the farmer and the environment. It is also important to examine the relationships between soil and plant N status and soil exchangeable Mo in these soils.

Most of the current rice breeding programmes are focused on improving the tolerance of new rice varieties to micronutrient deficiencies (Rashid and Ryan, 2008; Suriyagoda, 2022). This would also add benefit to farmers as newly developed rice varieties would not be affected by low soil Mo concentration. Even though the soil exchangeable Mo concentration was assessed in this study, the concentration of Mo in rice plants has not been tested. Therefore, the degree of Mo deficiency that prevails in Sri Lankan rice crops needs to be examined.

Conclusions

Exchangeable soil Mo concentration in lowland rice-cultivated soils in Sri Lanka was low. It was affected by ACZs, soil orders, water sources, and their interactions. Moreover, there was a spatial heterogeneity of soil Mo distribution, i.e. higher in WL among ACZs, and higher in Histosols among the soil orders tested. Higher Mo concentration was reported from rainfed paddy fields than that observed in irrigated paddy fields. Spatial maps of Mo were generated using a large number of samples in this study. Therefore, these maps could be used to identify the areas with low and high Mo levels in the country and make area-specific agronomic and administrative decisions. We also suggest identifying critical or threshold levels of exchangeable Mo concentration in paddy fields rather than soil total Mo or plant Mo concentrations. As the Sri Lankan rice soils tested contained low levels of exchangeable Mo, it is important to implement strategies to increase the exchangeable Mo concentration in soil to ensure high productivity in rice crops. Key mitigation strategies include liming of soil in the drier areas and the incorporation of organic matter into the sloppy lands of the Wet zone. In parallel, appropriate nutrient management, proper water management, and the development of Mo deficiency tolerant rice varieties through breeding would be needed to prevent yield loss in rice due to Mo deficiency. Therefore, an integrated approach with the contribution of all the stakeholders is needed.

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Author contributions. MA, UR, HK, RC, and LS designed the study, MA, RM, and LS collected field data, IH, UR, and RM did the laboratory analysis, LS did the data analysis, IH drafted the manuscript, and all the authors contributed to improve the manuscript.

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Competing of interests. The authors declare no competing interests.

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