RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2022.028

ScienceAsia 48 (2022): **223–230**

Magnesium fractionation in different textural groups and commercial crop cultivations of Thai soils

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Received 16 Jun 2021
Accepted 26 Oct 2021

ABSTRACT: Thai soils are dominated by extremely weathered and developed Ultisols that are characterized by acidity, low fertility, and high leaching of basic cations, including magnesium (Mg). In this study, the distribution of Mg chemical fractions in Thai soils and major commercial crop fields was assessed using sequential extraction. Moreover, the status of available soil Mg was estimated using single leaching. Similar distribution patterns of Mg fractionation in the inorganic soils and the commercial crop cultivation soils were noticed. The mean percentage distributions of Mg fractions spread in a decreasing magnitude: the mineral Mg > the available Mg > the carbonate Mg > the organic complexed Mg; and the recorded values were 68.43, 22.81, 5.90, and 2.86 in the inorganic soils and 69.67, 23.60, 4.52, and 2.21 in the commercial crop cultivation soils, respectively. A distinct Mg fractionation pattern occurred within organic soils with a spread percentage of 71.79, 14.68, 8.91, and 4.62 for available Mg, organic complexed Mg, mineral Mg, and carbonate Mg, respectively. The available Mg concentration within organic soils was 541.21 mg/kg; while the inorganic soils per textural group produced 510.86, 26.87, and 20.89 mg/kg in fine, medium, and coarse textured soils, respectively. Among the commercial crop cultivation soils, rice and coconut were grown in soils with adequate Mg; whereas oil palm, durian, longkong, and rubber were cultivated in Mg deficient soils. Mg is an essential element in plants; therefore, medium, coarse textured soils, and the extremely weathered tropical Ultisols, regardless of their texture, require Mg replenishment for optimum plant productivity within the tropics.

KEYWORDS: magnesium forms, sequential extraction procedure, soil texture, available-Mg

INTRODUCTION

Tropical soils are mostly acidic and infertile with low values of basic cation plant nutrients, such as magnesium (Mg), calcium (Ca), and potassium (K) [1]. High temperatures and rainfall that are common features in tropical climate result in excessive weathering and development of kaolinitic soils with high contents of aluminum and iron oxides, low pH, and low levels of macro- and micro-nutrients [1]. Thailand is situated in the tropical zone, with estimated annual mean temperature and rainfall around 28 °C and 1500 mm, respectively [2]. These weather conditions result in extensively weathered soils with high leaching potential. As a result, 40% of the Thai soils are classified as Ultisols [3] and exhibit poor soil fertility with low organic matter (OM) contents, low levels of basic cations, and kaolinite dominated clay mineralogy [4, 5]. Hence, the restoration of deteriorating soil fertility in Thailand focuses on mixed chemical fertilizers (N-P_2O_5-K_2O) without addition of Mg to boost agricultural productivity [6]. As a result, the available Mg is slowly decreasing, and Mg deficiency has been recorded in commercial crop production soils [7, 8]. Mg is an essential nutrient for plant growth, playing a vital role in several metabolic processes in the lifecycle of a plant while also serving in adaptive and protective roles in abiotic stress situations [9]. The availability of soil Mg depends on soil pH, soil texture, and the concentrations of competing cations [10].

Evaluation of soil Mg commonly employs the single extraction, a one-step extraction technique based on bioavailability [11]. The extraction divides bioavailable Mg chemical fractions reflecting the metal forms as water soluble Mg, exchangeable Mg, and mineral Mg [12]. Ammonium acetate (1 M NH_4OAc pH 7.0) is among the reagents used to extract and estimate available Mg (Avail-Mg) in the single extraction. Avail-Mg includes both the water soluble Mg and the exchangeable Mg, the fractions correlated with plant Mg uptake; and the 1 M NH_4OAc pH 7.0 gets a general approval because it is easily applied and tends to produce consistent results [13]. However, the single extraction scheme used for Mg fractionation analysis has limitations, as it gives little information about the soil environmental conditions and their effects on metal fractionation in soil. The sequential extraction process (SEP) can be used to address some of the limitations of the single extraction. The SEP estimates metal fractions in soil with the general purpose of selective extraction to simulate the release of the distinct metal forms into a solution under various environmental conditions [14]. It begins from the weakly bound fraction to the strongest crystalline structure, and using a range of reagents from the least hostile extractant to the most aggressive reagent [14]. Additional benefits of the SEP include clear outcome about the existence of distinct chemical forms of an element from the use of several reagents. The existence of each fraction, weather as bioavailable, acid-soluble, mineral, oxidizable or reducible forms, can be related to soil environmental conditions through the help of the SEP protocol [11, 15]. Moreover, prior to any remediation to replenish Mg in soil, the SEP can provide additional understanding of solubility, availability, and precipitation of Mg; and this information can enable reliable evaluation of the metal elements in soil [12]. Although the SEP was originally developed for the assessment of trace elements, the approach has already been accepted successful in evaluating other elements linked to soil fertility, such as P [16], Ca [17], K [11], and Mg [18, 19]. The fractionation of Mg in soil reveals different levels of Mg reserves in various forms of existence and, therefore, signifies the potential bioavailability of Mg in soil. The SEP allocates Mg into four forms as follows. (1) The available Mg (Avail-Mg), a fraction combining the water-soluble Mg (Mg in soil solution) and the exchangeable Mg that is a fraction weakly held within clay and humus particles but still in contact with soil solution and readily replaceable, and plants take up Mg in this form [18, 19]. (2) The organic complexed Mg (OM-Mg) is formed while the soluble Mg combines with organic ligands in the rhizosphere resulting in a slowly bioavailable Mg in a complexed form [18, 19]. (3) The carbonate/acid soluble Mg (Acid-Mg) is the fraction that is related to carbonate minerals; dolomite and magnesite are common Mg carbonates [19]. (4) The last fraction is the mineral Mg (Mineral-Mg), the fraction fixed in the crystalline soil minerals [19].

Information about the distribution of Mg chemical fractions in organic and inorganic Thai soils and their relationships with soil properties is very scarce. Therefore, an evaluation of Mg chemical fractions in organic soils and different textural groups of inorganic soils was essential. The resulting information can be used as a reference regarding the soil Mg reserves and quantities of different Mg forms in soil, and subsequently facilitate proper Mg fertilizer management for precision of agricultural practices. This study was carried out as an initial wide-ranging effort aimed to investigate the distribution of Mg fractionation in different textural groups of Thai inorganic soils, organic soils, and commercial crop cultivation soils.

MATERIALS AND METHODS

Sampling and sample preparation

Thai soils with varying physicochemical properties from various Thai soil orders were collected from the depth of 0–30 cm and grouped as inorganic soils (all soils except the suborder Histels and order Histosols) and organic soils that are characterized by Soil Taxonomy [24]. The inorganic soils were further subdivided into textural groups as fine, medium, and coarse textured soils. The fine textured soil group (n=10) included the soil series of Pak Chong:Pc, Ao Luek:Ak, Lop Buri:Lb, Hat Yai:Hy, Ruso:Ro, Klaeng:Kl, Bangkok:Bk, Takhli:Tk, Munoh:Mu, Tha Chin:Tc, and Lam Narai:Ln. The medium textured soil group (n=6) included Phuket:Pk, Fang Daeng:Fd, Sawi:Sw, Visai:Vi, and Nam Kracha:Ni. Lastly, the coarse textured soil group (n=5) comprised Kho Hong:Kh, Khok Khain:Ko, Tha Sae:Te, Thung Wa:Tg, and Bacho:Bc. Organic soils (n=2) from Daeng:Kd and Narathiwat:Nw were also covered in this study (Table S1). Additional 30 soil samples, five each from 6 major commercial crop fields in Thailand representing rubber, coconut, oil palm, longkong, durian, and rice, were also used. The soil samples were air-dried, ground, and passed through a 2-mm sieve for determining soil basic properties, with a further subsample passed through a 0.50 mm sieve for Mg fractionation analysis and organic matter content.

The physicochemical properties analysis

The physicochemical properties of the soil samples were determined following standard methods [13]. Soil pH and electrical conductivity (EC) were measured in the supernatant of 1:5 (w/v soil:deionized water). Organic matter was determined using Walkley and Black method. The Bray II procedure was applied to establish the available phosphorus (Avail. P). Total nitrogen was evaluated by Kjeldahl method. A 1 M NH_4OAc solution pH 7.0 was used to saturate the exchange sites for the estimation of cation exchange capacity (CEC), the supernatant was used to estimate extractable K, Ca, and Mg (Extr. K, Ca, and Mg), and the soil texture was assessed following the pipette method [20].

Magnesium speciation analysis

The SEP was used to determine Mg chemical fractions, and each sample was replicated 3 times. A 1.00-gram (g) soil sample was subjected to an uninterrupted four step sequence of extractions for Avail-Mg, OM-Mg, Acid-Mg, and Mineral-Mg with the respective extractants and conditions (Table 1). Each suspension was centrifuged at relative centrifugal force (RCF) of 1588 g and the supernatant was decanted and passed through a Whatman No. 5 filter paper into polythene plastic bottles. The sample was double washed with deionized water and solutions were discarded prior to the next reagent use. Finally, the residue from preceding extraction was transferred into a 50 ml beaker where it was oven dried for 24 h. The dried sample was digested with 25 ml tri-acid mixture (HNO_3:$HClO_4$:H_3PO_4) at the percentage ratio of 23:54:23 v/v on a hotplate at 150 °C until soil particles changed to white.

All the supernatants were analyzed for Mg fraction concentrations by Atomic Absorption Spectrophotometer (AAS; iCE 3000 series, Thermo Scientific, USA). For

Table 1 Sequential extraction procedure for Mg fractionation [19].

Step	Form/association	Extraction reagent	Activity	Time (min)	Temp (°C)	Final volume (ml)
1	Available Mg	25 ml of 1 M NH_4OAc pH 7.0	Shaking	60	25	25
2	Organic complexed Mg	10 ml of 10% H_2O_2	Shaking	120	25	10
3	Acid-soluble Mg	30 ml of 1M HNO_3, adjust with 0.2 M HNO_3 to 50 ml	Boiling	15	85	50
4	Mineral Mg	25 ml of triacid mixture,* 5 ml of 5 M HCl after decanting and adjust to 25 ml with DI water.	Heating	90–120	150	25

* Tri-acid mixture = $HNO_3 + HClO_4 + HPO_4$ at 23%:54%:23% v/v.

quality and accuracy control, a single digestion step for total-Mg was carried out and used to calculate the percentage of Mg recovery

$$\text{Mg recovery }(\%) = \frac{\sum_n \text{Mg fractions}\,(\text{pseudo} - \text{total-Mg})}{\text{total-Mg}} \times 100$$

where $\sum_n$ is the sum concentration of Mg species from individual steps for (pseudo—total-Mg), and total-Mg was a single tri-acid mixture digestion soil Mg concentration value [11]. In this study Mg concentration recovery based on SEP analysis was accepted within 15% error.

Percentage was used for the separation of Mg distributions in different soil types, between textural groups and commercial crops. Pearson correlation analysis at 5% and 1% significance level was used to assess the interrelations between Mg species and the different soil properties.

RESULTS

Soil physicochemical properties

Inorganic and organic soils showed soil pH ranging from strongly acidic (3.66) to slightly alkaline (8.05) (Table 2 and Table 3). Maximum CEC in the inorganic and the organic soils were 54.25 and 104.75 $cmol_c$/kg, respectively. The OM percentages in some inorganic soils were higher than normal with the ranges of 9.95–56.92 g/kg for fine, 8.50–11.98 g/kg for medium, and 6.01–13.37 g/kg for coarse textured soils. However, OM content was smaller in the inorganic soils (6.01–56.95 g/kg) than in the organic soils (432–448 g/kg) as expected.

Distribution of Mg chemical fractions in soils

The mean total Mg concentrations in organic and inorganic soils were 606.10 and 707.83 mg/kg, respectively (Table S3). In the inorganic soils, the percentages of Avail-Mg were in a descending range of 40.45, 16.02, and 11.96% for fine, medium, and coarse textured soils, respectively (Fig. 1a). The mineral-Mg fractions in medium, coarse, and fine soils were calculated at 82.35, 76.12, and 46.81%, respectively. The OM-Mg generated an average value of just 2% in the

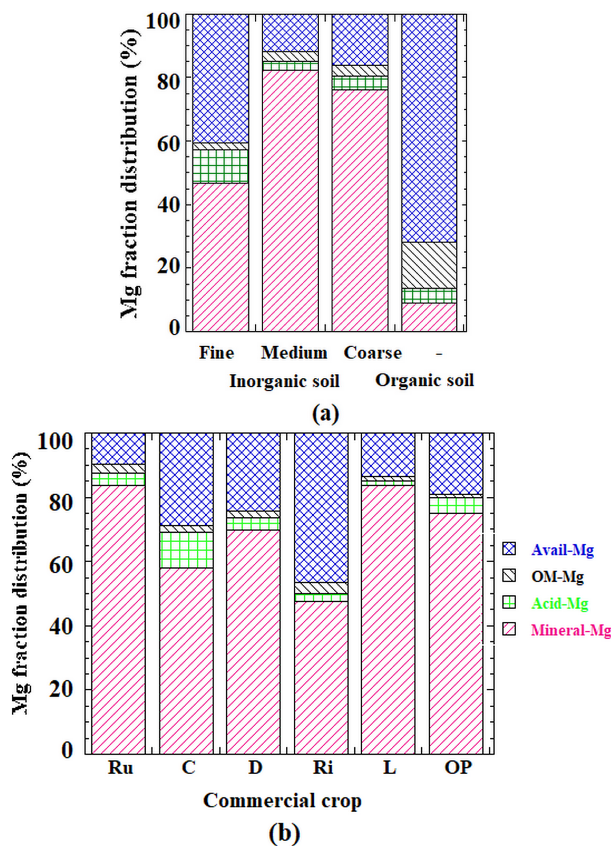

Fig. 1 Mg chemical fractions in Thai soil series (a) and commercial crop cultivation soils (b). Note: Ru = rubber, C = coconut, D = durian, Ri = rice, L = longkong, OP = oil palm.

inorganic soils. The Acid-Mg was distributed within 10.60% of the total Mg distribution in fine textured soils and an average of 5% in both the medium and the coarse textured soils. In the organic soils, the percentages of Mg fraction were in descending order of Avail-Mg > OM-Mg > Mineral-Mg > Acid-Mg at 71.79, 14.68, 8.91 and 4.62%, respectively. In this study, the commercial crop cultivation soils properties (Table 3)

Table 2 The physicochemical properties of inorganic and organic Thai soils.

Soil property	Inorganic soil (n=21)						Organic soil (n=2)	
	Fine textured (n =10)		Medium textured (n = 6)		Coarse textured (n = 5)		-	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
pH (1:5 soil:water)	3.66–8.05	6.24	4.34–5.35	4.84	5.07–5.37	5.21	3.78–4.01	3.89
EC (dS/m)	0.02–8.67	1.00	0.02–0.07	0.04	0.01–0.03	0.02	0.12–0.12	0.12
OM (g/kg)	9.95–56.92	22.63	8.50–11.98	10.36	6.01–13.37	10.96	432.0–448.1	440.00
Total N (g/kg)	0.51–1.90	1.09	0.34–0.78	0.57	0.37–0.71	0.53	8.01–9.38	8.69
Avail. P (mg/kg)	3.02–31.04	13.01	3.89–9.88	7.50	4.30–17.52	7.97	5.72–11.06	8.39
CEC ($cmol_c$/kg)	1.40–54.25	20.53	1.20–4.43	3.01	1.11–4.36	2.54	85.39–104.75	95.07
Extr. K^*(mg/kg)	15.68–876.63	135.63	7.21–52.75	20.43	4.89–15.15	10.03	19.85–321.30	170.57
Extr. Ca^*(mg/kg)	12.4–13149.5	5367.31	18.56–62.18	74.19	21.92–112.98	42.00	602.39–877.63	740.01

Range shows minimum and maximum values, * extracted using 1 M NH_4OAc pH 7.0.

Table 3 Basic physicochemical properties of commercial crop cultivation soils.

Crop	pH (1:5)	EC (dS/m)	Total N (g/kg)	OM (g/kg)	Avail. P (mg/kg)	Extr. Ca (mg/kg)	Extr. K (mg/kg)	Sand (%)	Clay (%)	Silt (%)	Textural class	Textural group
Rubber (n=5)	5.3	0.02	0.82	16.96	26.1	75.5	29.8	46	28	28	SCL	Coarse
Coconut (n=5)	6.8	0.04	1.00	20.95	13.0	1820.4	95.8	59	26	15	SCL	Coarse
Durian (n=5)	5.0	0.04	0.62	14.97	28.6	123.8	93.0	62	17	21	SL	Coarse
Rice (n=5)	4.8	0.25	0.66	16.92	13.2	565.6	158.6	5	38	57	SiC	Fine
Longkong (n=5)	4.7	0.04	1.01	21.95	24.2	150.3	62.7	55	32	13	SCL	Coarse
Oil palm (n=5)	4.1	0.19	1.32	27.94	4.0	187.6	31.5	39	28	34	L	Medium

SCL = sandy clay loam, SL = sandy loam, SiC = silty clay, L = loam.

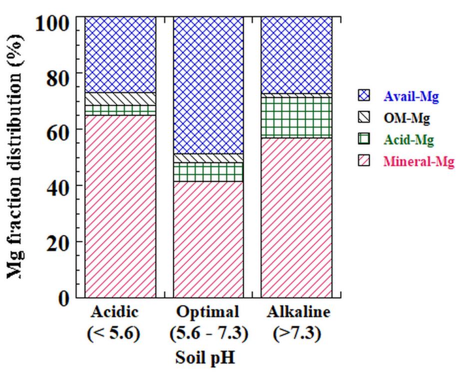

Fig. 2 Mg chemical fractions in Thai soils series based on soil pH.

categorized them within mineral soils as classified by Soil Taxonomy [24]. The joint order and magnitude of Mg fractionation results closely matched those from Thai soil series characterized through soil taxonomy, the Mineral-Mg range (47.66–88.77%) covered the largest percentage of the fractionation distribution, followed by Avail-Mg (5.48–46.33%), Acid-Mg (1.52–8.65%) and OM-Mg (1.52–4.19%) (Fig. 1b). The percentage of Avail-Mg was highest in rice growing soils at 46.33 followed by coconut growing soils with 30.42. Lastly, OM-Mg in all soils was below 5% while Acid-Mg was highest in coconut growing soils at 8.67%.

Mg speciation based on soil pH category (Fig. 2) indicated that the Avail-Mg dominated in optimal soil pH (48.90%), while both acidic and alkaline soils yielded around 27% of the Avail-Mg. The Acid-Mg increased with soil pH as depicted by percentages of 3.71, 6.51, and 14.39 in acidic, optimal, and alkaline soil pH, respectively.

Available Mg status in soils

The Avail-Mg concentrations from 1 M NH_4OAc pH 7.0 extraction were high in the fine textured soils (510.86 mg/kg) and the organic soils (541.21 mg/kg), while lower concentrations were observed in the medium (26.86 mg/kg) and the coarse textured (20.89 mg/kg) soils, (Fig. 3a). Longkong, oil palm, rubber, and durian growing soils produced low contents of Avail-Mg ranging within 20.13–60.90 mg/kg and revealed low concentration relative to the Mg optimal level (Fig. 3b). In the contrary, high Avail-Mg was found in rice growing soils (466.53 mg/kg), while coconut growing soils produced moderate concentration (173.64 mg/kg) of Avail-Mg.

The correlations between the soil Mg fractionation and the soil properties

Significant correlations within the fractionation of Mg (Table 4) and the several soil properties (Table 5) were observed. The Avail-Mg correlated strongly with clay particles (r = 0.723**). OM-Mg displayed moderate positive correlation with OM (r = 0.620**) and total N (r = 0.643**); and strong correlation with CEC (r = 0.808**). The Acid-Mg had significant correlation with soil pH (r = 0.760**). The majority of Mg

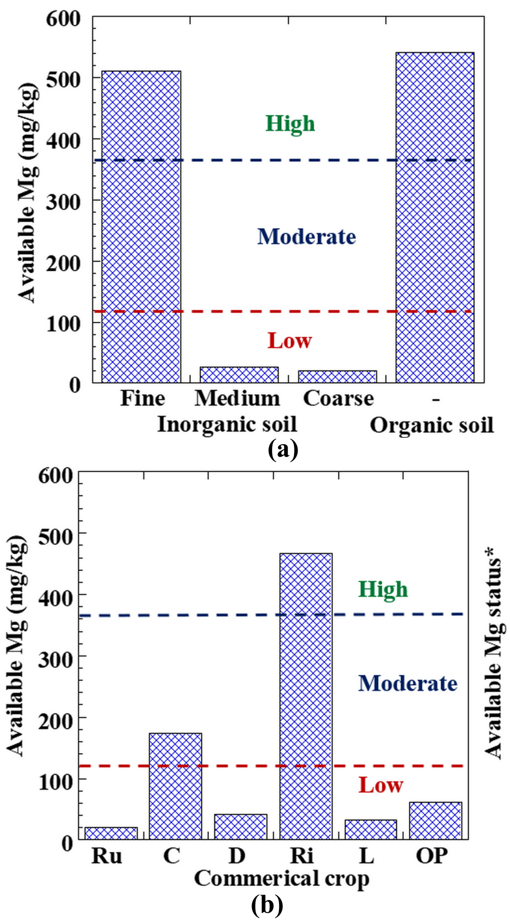

Fig. 3 Available Mg status in Thai soil series (a) and in commercial crop cultivation soils (b). Note: Ru = rubber, C = coconut, D = durian, Ri = rice, L = longkong, OP = oil palm. * Available Mg status (low < 122 mg/kg, moderate 122–365 mg/kg, high > 365 mg/kg) based on Department of Land Development [21].

Table 4 The correlation coefficients (r) in Mg fractionation in Thai soils.

Mg speciation	Avail-Mg	OM-Mg	Acid-Mg	Mineral-Mg
OM-Mg	0.660**			
Acid-Mg	0.537**	0.486*		
Mineral-Mg	0.397	0.111	0.805**	
Total-Mg	0.742**	0.468*	0.893**	0.805**

*,** Correlation is significant at $p \leqslant 0.05$ or 0.01, respectively.

forms generated positive significant correlations with clay particles and negative significant correlations with sand particles (Table 5).

DISCUSSION

Soil physicochemical properties

Soil pH range stayed within the acidic status in organic and inorganic soils (Table 2), and this indicated the prevalence of acidity within Thai soils. These results align with a general view that the majority of tropical soils are acidic in nature [22]. The contents of OM, total N, available P, and CEC were low in inorganic soils. Similarly, commercial cultivation fields displayed parallel physicochemical properties, except for the coconut growing soils that demonstrated higher soil pH (close to neutral) at pH 6.84 (Table 3). Similar results have been reported for rubber growing soils that were acidic with low salinity and OM content, and infertile with low values of CEC [23]. Thai commercial crops are grown in coarse textured soils, excluding oil palm and rice, which are both farmed in medium and fine textured soils. The Ln and Tk soils with average CEC of over 40 $cmol_c$/kg and pH above 8.0 were Mollisols displaying surface soil characteristics of high base cation saturation. Mollisols have a base saturation of over 50% in the epipedon [24]; hence, they also revealed a high Mg content. The Lb soil represents Vertisols with high soil pH (7.26) and CEC (54.25 $cmol_c$/kg) (Table S1 and Table S2). The Tc soil exhibited high salinity (8.66 dS/m) and Ca (8572 mg/kg) represents Entisols (Table S1 and Table S2). Tc soil series is formed from marine sediments practically waterlogged with sea-water and has an alkaline pH and high salinity [3, 25]. The Organic soils (Histosols) produced comparatively high OM (440 g/kg) and CEC (95.07 $cmol_c$/kg), consistent with the classification of organic soils, and the Thai organic soils' OM content assigns them to peat soils with OM above 300 g/kg [26].

In the inorganic soils, the Mg chemical fraction distribution of the Mineral-Mg, Avail-Mg, Acid-Mg, and OM-Mg were 46.81, 40.44, 10.60, and 2.15% in the fine textured soils; 82.35, 11.96, 2.61, and 3.08% in the medium textured soils; and 76.12, 16.02, 4.51, and 3.35% in the coarse textured soils; respectively. In summary, the observed Mg fractionation rank order was Mineral-Mg > Avail-Mg > Acid-Mg > OM-Mg, estimated collectively at 68.43, 22.81, 5.90, and 2.86%, respectively. These results slightly differ from the order of previous studies, Mineral-Mg > Acid-Mg > Avail-Mg > OM-Mg [18]. In contrast, the organic soils produced an altered order of the Mg fractionation ranks as Avail-Mg > OM-Mg > Mineral-Mg > Acid-Mg with the fractionation distribution of 71.79, 14.68, 8.91, and 4.62%, respectively. Organic soils develop from the decomposition of plant litters; and, therefore, the presence of different binding sites in the soil leads to the formation of various Mg-organic complexes, resulting in increased OM-Mg (Fig. 1a). Soluble metal organic complexes accelerate metal diffusion in soils [27]. The elevated OM-Mg in organic soils was established as the

Table 5 The correlation coefficients (r) between the Mg fractionation and the soil properties.

Soil property	Avail-Mg	OM-Mg	Acid-Mg	Mineral-Mg	Total-Mg
pH	0.234	0.080	0.760**	0.662**	0.640**
EC	0.730**	0.114	0.095	0.292	0.409*
OM	0.229	0.620**	−0.045	−0.168	−0.059
Avail. P	0.593**	0.276	0.652**	0.684**	0.689**
Total N	0.276	0.643**	0.001	−0.090	−0.083
CEC	0.447*	0.808**	0.455*	0.284	0.382
Extr. K	0.783**	0.352	0.196	0.343	0.461*
Extr. Ca	0.596**	0.393	0.960**	0.849**	0.906**
Sand (%)	−0.595**	−0.432*	−0.538**	−0.660**	−0.648**
Clay (%)	0.723**	0.588**	0.714**	0.660**	0.772**
Silt (%)	0.215	0.085	0.121	0.400	0.253

*, ** Correlation is significant at $p \leqslant 0.05$ or 0.01, respectively.

direct reserve fraction to restock the available Mg.

The largest component of soil Mg was the Mineral-Mg in the inorganic soils (Fig. 1a and Fig. 1b). The bulk of soil Mg (around 90%) is strongly fixed in the lattice structure of clay minerals and, as a result, inaccessible to sustain plant life [9]. High concentration of Avail-Mg was found in the fine textured and the organic soils, which is consistent with the existing information that fine textured soils hold large amounts (51–70%) of soil Mg [10]. Additionally, higher levels of Avail-Mg in soils are found in clay soils. Clay particles are the source of negative charge to adsorb cations, such as Mg^{2+}. Moreover, clay particles are important as a source of both primary Mg mineral (ferromagnesian clay mineral e.g. biotite and hornblende) and secondary Mg mineral (2:1 clay mineral e.g. vermiculite, montmorillonite, and saponite) [28, 29]. Primary and secondary Mg mineral can release Mg and enhance soil Mg level. On the other hand, sand fraction normally lacks Mg-bearing minerals and exhibits a low negative charge; thus, a course texture soil has lower Avail-Mg and total-Mg than a fine texture soil. The positive relationships of Avail-Mg, Acid-Mg, and Mineral-Mg with clay particles, Extr. Ca, and Avail. P (Table 5) somehow affirmed coexistence of Mg, Ca, and P clay minerals in most Thai soils. Moreover, most Mg was found in young clay soils in Entisols (Tc soil series) which also demonstrated higher OM content. The Mollisols (Ln and Tk soil series) with a mollic epipedon were characterized by high base saturation. The Vertisols (Lb) with high soil pH and CEC (Table S2 and Table S3) equally illustrated high Mg content compared with the Ultisols, the main Thai soil series. These results demonstrate that soil Mg fertilization should be considered for the Thai Ultisols irrespective of their texture since they contain low available Mg. However, Thai Mollisols, Histosols, and a few young clay soils (at early stages of development like Entisols and Vertisols with higher soil pH and CEC) contain enough Mg to sustain plants.

The OM-Mg was below 4% in mineral soils, and 43% of Thai soils have very low soil OM and CEC [30]. Moreover, the weak relationship between Mg fractions and CEC (Table 5) indicated low CEC in Thai soils, resulting in a low capacity to form complexes with Mg. These results are reminiscent to previous reports in which OM-Mg contributes a diminutive fraction (< 5%) in total Mg fractionation in the soil [18]. However, in this study, the OM-Mg was elevated in the organic soils (14.68%), perhaps, as a direct gain from the increased OM (440 g/kg) within the soils (Table 2). OM is a source of plant nutrients, and the decomposition of litter is accelerated by elevated temperature and moisture resulting in increased Mg and other plant nutrient levels in soils [31]. Moreover, the significant positive correlations of OM-Mg with total-N (r = 0.643**) and OM (r = 0.620**) (Table 5) illustrated the concurrent existence of both the OM-Mg and the N in decomposed plant materials. Mg is estimated around 0.86–3.88 g/kg in plant dry matters [10].

The acid soluble Mg fraction, Acid-Mg, is associated with carbonates, and the Mg content bound to carbonates is sensitive to pH changes and is extracted when soil pH is lowered [32]. The study results showed that an increase in soil pH to alkalinity was associated with higher content of Acid-Mg (Fig. 2) and strong positive correlations with soil pH of Acid -Mg (r = 0.760**) and Extr. Ca (r = 0.960**) (Table 5). The observed minor proportion of Acid-Mg in this study indicated the constrained presence of carbonates in the tropics, as carbonates are commonly found in dry semi-arid and arid areas with low rainfall where Calcisols are dominant [33]. In addition, the negative significant correlations between Mg chemical fractions and sand particles indicated that a higher content of sand in soil likely lowered the Mg reserves in soil [34].

The optimal level of available Mg range for Thai soils is 122–365 mg/kg [21] (Fig. 3). A high Avail-Mg contents in the the fine textured and organic soils were noted. Besides, significant positive correlations between Avail-Mg and OM-Mg (r = 0.660**) (Table 4) and clay particles (r = 0.723**) (Table 5) were observed. This connection could be related to the clay-humus complex, the soil colloids with charges for cation adsorption and, therefore, holding a substantial amount of Avail-Mg. The available Mg fraction comprises a cationic Mg that is electrostatically adsorbed to negatively charged soil particles [33], and these results reveal that Thai medium and coarse textured soils with less clay content require addition of organic fertilizers to improve their colloidal soil component to hold more available Mg.

Moderate Avail-Mg content was observed in coconut growing soils despite their coarse nature (Fig. 3b). This may be supported by the main environment type where Thai coconut is grown along the coastal regions where alkaline and saline soils with high contents of base cations prevail, and they also exhibit a high soil pH (Table 3). Low concentrations of Avail-Mg were observed in medium and coarse textured soils (Fig. 3a). These results agree with previous information that clay soils contain adequate exchangeable Mg for plant requirements [9]. However, some Ultisols clay soils, such as Hy, Kl, and Ro (Table S3) and sandy soils, showed low amounts of Avail-Mg and, therefore, required Mg replenishment.

In commercial crop cultivation soils, the Avail-Mg content was in descending order of rice > coconut > oil palm > durian > longkong > rubber. These results show that only rice and coconut were grown in soils with sufficient Mg contents of high and moderate Mg concentrations, respectively. In contrast, oil palm, durian, longkong, and rubber are grown in Mg deficient soils (Fig. 3b). Similar results for the rank order of available Mg in Thai main commercial crop fields have been observed in previous studies [35]. Rice is grown in fine clay soils with high Mg and clay minerals, while coconut is grown in alkaline soils with higher pH and higher Mg quantities. The rest of the crops are grown in medium and coarse textured soils with low levels of Avail-Mg. Therefore, Thai soils with low available Mg below 122 mg/kg [21] should be restocked with Mg sources (like kieserite or dolomite) to increase soil Mg. The application of these Mg sources does not only supply Mg but also promotes plant growth and production, similar to what has been demonstrated in rice [36].

Most of Mg within the inorganic soils is contained in soil minerals, while the available Mg is the dominant fraction in the organic soils. The available Mg exists in abundance within the soil colloids. As a result, the fine mineral soils and the organic soils hold enough Mg for plants. The carbonate and organic complexed Mg rose with soil pH and OM content, respectively. Mg fertilization should be considered for rubber, durian, oil palm, and longkong that are cultivated predominantly in medium and coarse textured soils with low available Mg. The scale of various Mg forms to replenish available Mg is not clearly known; therefore, future assessment of the trend is essential for proper estimates of available Mg.

Appendix A. Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.2306/scienceasia1513-1874.2022.028.

Acknowledgements: This research was financially supported by the Prince of Songkla University, Graduate School, Hat Yai, Songkhla, Thailand.

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Appendix A. Supplementary data

Table S1 Soil texture of inorganic and organic Thai soils taxonomy classification.

Soil type	Textural group	Soil series	Sand (%)	Clay (%)	Silt (%)	Textural class	Soil taxonomy classification	Soil order
Organic		Nw	–	–	–	–	Dysic, isohyperthermic Typic Haplofibrists	Histols
		Kd	–	–	–	–	Loamy, mixed, superactive dysic,isohyperthermic Terric Sulfihemists	Histols
Inorganic	Fine	Pc	12	40	48	SC	Very fine, kaolinitic, isohyperthermic Rhodic Kandiustox	Oxisols
		Ak	16	68	16	C	Very fine, kaolinitic, isohyperthermic Rhodic Kandiudoxs	Oxisols
		Lb	7	68	25	C	Very fine, kaolinitic, isohyperthermic Rhodic Kandiudoxs	Vertisols
		Hy	76	12	12	SL	Very fine, smectitic, isohyperthermic Typic Haplusterts	Ultisols
		Ro	41	16	43	L	Clayey-skeletal,kaolinitic, isohyperthermic Typic Paleudults	Ultisols
		Kl	20	24	56	SiL	Very fine, kaolinitic, isohyperthermic Typic Plinthaquults	Ultisols
		Bk	3	44	53	SC	Very fine, smectitic, nonacid, isohyperthermic Vertic Endoaquepts	Vertisols
		Mu	12	44	44	SC	Fine, mixed, semiactive, acid, isohyperthermic Sulfic Endoaquepts	Vertisols
		Tc	3	56	41	SC	Fine, smectitic, nonacid, isohyperthermic Sodic Hydraquents	Entisols
		Ln	6	52	42	SC	Fine, smectitic, isohyperthermic Vertic Haplustolls	Mollisols
		Tk	16	48	36	C	Loamy-skeletal, carbonatic, isohyperthermic Entic Haplustolls	Mollisols
	Medium	Pk	74	16	10	SL	Fine, kaolinitic, isohyperthermic Typic Kandiudults	Ultisols
		Fd	53	16	31	SL	Fine-loamy, kaolinitic, isohyperthermic Rhodic Kandiudults	Ultisols
		Sw	36	12	52	SiL	Loamy-skeletal, mixed, semiactive, isohyperthermic Typic Paleudults	Ultisols
		Vi	22	20	58	SiL	Fine-loamy, mixed, semiactive, isohyperthermic Typic Plinthaquults	Ultisols
		Ni	62	12	26	SL	Fine, mixed, semiactive, isohyperthermic Typic Haplohumults	Ultisols
	Coarse	Kh	76	8	16	SL	Coarse-loamy, kaolinitic, isohyperthermic Typic Kandiudults	Ultisols
		Ko	79	12	9	SL	Fine-loamy, kaolinitic, isohyperthermic Typic Kandiaquults	Ultisols
		Te	66	24	10	SCL	Fine-loamy, kaolinitic, isohyperthermic Typic Kandiudults	Ultisols
		Tg	83	8	9	LS	Coarse-loamy, siliceous, subactive, isohyperthermic Typic Paleudults	Ultisols
		Bc	91	4	5	S	Coated, isohyperthermic, Typic Quartzipsamments	Inceptisols

C = clay, L= loam, S= sand, SCL = sandy clay loam, SL = sandy loam, SC = silty clay, SiL= silty loam, and LS= loamy sand. Soil Classification based on Land Development Department [25].

Table S2 Physiochemical properties of Thai soil series.

Soil type	Texture group	Soil series	pH	EC (ds/m)	OM (g/kg)	Avai. P (mg/kg)	Total N (g/kg)	CEC ($cmol_c$/kg)	Extr. K (mg/kg)	Extr. Ca (mg/kg)
Organic	–	Nw	4.01	0.12	432.00	5.63	8.01	85.39	19.85	602.39
		Kd	3.78	0.12	448.08	11.06	9.38	104.75	321.30	877.63
Inorganic	Fine	Pc	5.71	0.07	17.88	9.37	1.13	10.53	83.78	1,707.26
		Ak	7.50	0.14	12.28	6.70	1.01	10.77	32.05	4,013.02
		Lb	7.26	0.14	12.60	18.20	0.54	54.25	30.47	13,149.53
		Hy	5.61	0.02	13.99	5.25	0.51	1.40	15.68	12.45
		Ro	5.42	0.03	9.95	3.39	0.72	4.15	16.48	475.53
		Kl	4.88	0.06	13.03	7.41	0.80	4.06	30.48	376.01
		Bk	5.09	0.04	15.47	4.84	0.94	11.08	66.82	592.97
		Mu	3.66	2.51	56.92	4.67	1.78	18.63	133.99	243.86
		Tc	6.03	8.66	52.68	34.70	1.90	17.17	873.63	8,572.21
		Ln	7.97	0.12	26.79	24.95	1.38	44.97	98.88	13,130.68
		Tk	8.05	0.11	17.35	27.22	1.36	40.47	154.10	11,248.74
	Medium	Pk	5.31	0.02	8.92	4.54	0.34	1.20	8.72	71.03
		Fd	5.03	0.03	8.51	8.86	0.50	1.58	7.21	36.61
		Sw	4.85	0.04	11.02	6.80	0.61	3.92	22.01	162.18
		Vi	4.71	0.03	10.02	6.96	0.78	4.43	18.38	92.51
		Ni	4.34	0.07	11.68	10.40	0.60	3.76	13.50	18.56
	Coarse	Kh	5.16	0.02	12.89	5.46	0.63	3.58	10.84	21.92
		Ko	5.33	0.02	6.01	8.26	0.37	1.46	4.89	112.98
		Te	5.13	0.02	13.37	5.30	0.71	4.36	10.64	24.64
		Tg	5.37	0.01	13.29	4.33	0.52	2.21	15.15	26.02
		Bc	5.07	0.03	9.22	20.14	0.43	1.11	8.63	24.43

Table S3 Concentrations of Mg fractions in Thai soil series.

Soil type	Textured group	Soil sample	Available Mg (mg/kg)	Organic complexed Mg (mg/kg)	Acid soluble Mg (mg/kg)	Mineral Mg (mg/kg)	Psuedo total Mg (mg/kg)	Total Mg (mg/kg)	Total Mg average (mg/kg)
Organic	-	Nw	259.77	45.87	8.73	60.25	337.49	314.95	606.10
		Kd	816.00	175.46	60.95	74.08	1011.98	897.25	
Inorganic	Fine	Pc	146.46	25.20	14.55	186.94	373.15	369.99	707.83
		Ak	387.93	10.13	91.47	159.52	649.05	617.04	
		Lb	1403.44	145.94	395.66	616.02	2561.06	2974.32	
		Hy	38.25	4.56	9.21	81.92	133.94	124.38	
		Ro	123.75	10.79	13.87	274.27	422.68	453.20	
		Kl	66.92	18.98	10.26	244.07	340.23	333.75	
		Bk	576.35	11.25	43.12	420.13	1050.85	986.42	
		Mu	499.67	9.54	27.47	733.35	1270.04	1290.60	
		Tc	1856.04	50.13	112.02	716.73	2734.92	2667.45	
		Ln	328.40	25.18	355.08	1438.23	2146.90	2318.83	
		Tk	200.73	14.44	237.27	1087.74	1540.18	1763.44	
	Medium	Pk	15.53	3.36	8.35	102.77	130.02	116.63	
		Fd	20.96	3.62	4.84	59.79	89.22	79.78	
		Ntn	33.07	6.61	6.30	173.35	219.33	194.98	
		Sw	52.23	7.55	7.00	143.12	209.90	213.10	
		Vi	21.71	5.11	7.06	183.84	217.72	199.07	
		Ni	15.62	4.99	4.99	161.06	186.65	173.39	
	Course	Kh	14.82	5.69	5.69	90.62	116.82	102.65	
		Ko	24.89	5.84	5.84	86.64	123.20	109.49	
		Te	18.38	6.54	6.54	136.78	168.23	176.28	
		Tg	27.17	7.32	7.32	133.56	175.35	193.71	
		Bc	19.74	5.70	5.70	95.35	126.48	113.72	