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Large-scale assessment of soil exchangeable magnesium and crop response to Mg fertilization in Fujian Province, a subtropical region of China

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KEYWORDS

Exchangeable magnesium, magnesium fertilization, spatial heterogeneity, soil properties, crop yield, Fujian Province

HIGHLIGHTS

- Mean soil ex-Mg was 83.8 mg·kg^{-1} in Fujian, with 81.5% below 120 mg·kg^{-1} threshold.
- Spatial pattern shows higher ex-Mg in downstream plains, lower in mountainous.
- Soil ex-Ca, precipitation, and soil pH were key factors regulating ex-Mg spatial variation.
- Mg fertilization increased yields by 5.3%–22.2%, NUE by 5.6%–10.8% across eight crops.
- Mg should be incorporated into regional nutrient and site-specific fertilization management.

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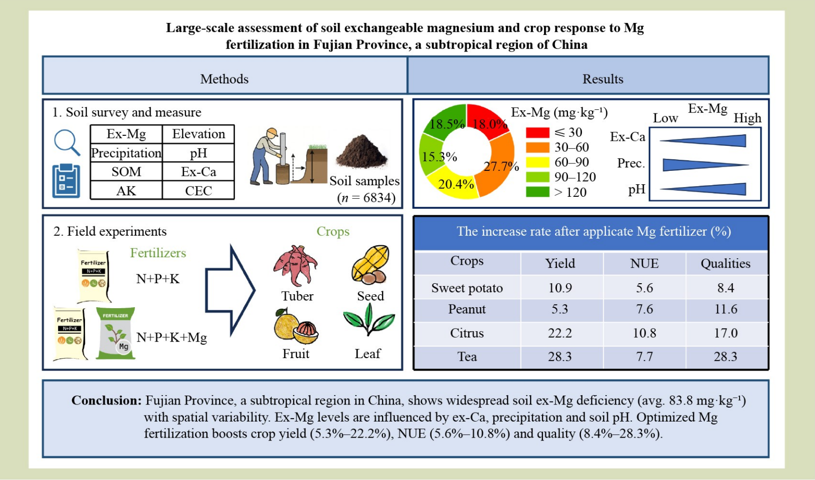
GRAPHICAL ABSTRACT



The increase rate after applicate Mg fertilizer (%)

Crops	Yield	NUE	Qualities
Sweet potato	10.9	5.6	8.4
Peanut	5.3	7.6	11.6
Citrus	22.2	10.8	17.0
Tea	28.3	7.7	28.3

Conclusion: Fujian Province, a subtropical region in China, shows widespread soil ex-Mg deficiency (avg. 83.8 mg·kg^{-1}) with spatial variability. Ex-Mg levels are influenced by ex-Ca, precipitation and soil pH. Optimized Mg fertilization boosts crop yield (5.3%–22.2%), NUE (5.6%–10.8%) and quality (8.4%–28.3%).

ABSTRACT

Soil exchangeable magnesium (ex-Mg) deficiency is increasingly recognized as a critical limitation for crop production in subtropical regions. This study focused on Fujian Province, a representative subtropical region in China, to identify the key determinants of soil ex-Mg using a large-scale survey of 6833 soil samples. Field experiments were also conducted to evaluate the effects of Mg fertilizer application on eight crops, including cauliflower, sweet potato, peanut, soybean, citrus, tea, potato, and sweet corn. Results showed that the average soil ex-Mg concentration across Fujian was 83.8 mg·kg^{-1}, with 81.5% of samples below the established sufficiency threshold of 120 mg·kg^{-1}. A clear spatial pattern was observed, with higher ex-Mg levels in downstream plains and substantially lower concentrations in upstream mountainous areas. Random forest analysis revealed that soil exchangeable Ca, precipitation, and soil pH were the primary factors influencing soil ex-Mg concentration. Field experiments demonstrated that supplementary Mg fertilization increased crop yields by 5.3%–22.2%, nitrogen uptake efficiency by 5.6%–10.8%, and quality indicators by 8.4%–28.3%. These findings highlight the importance of incorporating Mg into regional nutrient management strategies to mitigate widespread Mg deficiency and enhance sustainable crop production in subtropical regions.

1 Introduction

Magnesium (Mg) is an essential macronutrient for plant growth and development. It plays fundamental roles in chlorophyll formation, photosynthetic carbon assimilation, enzyme activation, the synthesis of structural compounds, and the transport and utilization of carbohydrates in plants[1–4]. In agricultural soils, soil exchangeable magnesium (ex-Mg) represents the major Mg pool readily available for root uptake, and is therefore widely used as a key indicator of soil Mg nutritional status and fertilizer effectiveness[5]. However, intensified cropping, soil acidification, and shifts in land use and fertilization practices have aggravated ex-Mg deficiency in many farming systems, resulting in losses in crop yield and quality[6–8]. Despite the growing recognition of Mg's importance, large-scale assessments that simultaneously characterize regional ex-Mg status and relate it to agronomic performance remain scarce. This knowledge gap limits the development of effective Mg management strategies at the regional level.

Considerable attention has therefore been directed toward the factors regulating soil ex-Mg. Among these, climate exerts a strong influence on ex-Mg distribution. In arid or cold regions, such as northern China, soil ex-Mg concentrations tend to be higher, whereas in warm and humid southern regions, they are generally lower[9]. High precipitation can accelerate Mg leaching and thereby reduce soil Mg availability, although it may also transiently increase Mg solubility under certain conditions[10]. Topography and elevation also contribute to spatial variation of soil ex-Mg. As elevation increases, soil ex-Mg concentration typically decreases[11]. For instance, Kanarek et al. reported that soil ex-Mg concentrations at the bottom of hills were 16.4% higher than at hilltops[12]. In addition, soil physicochemical properties strongly affect ex-Mg retention and mobility. Clay soils, with higher cation exchange capacity (CEC), retain more Mg^{2+}, while sandy soils, with faster drainage, are more susceptible to Mg^{2+} leaching[13]. Human activities further modify soil Mg status. In particular, long-term intensive NPK fertilization, insufficient Mg replenishment, and progressive soil acidification can accelerate depletion of ex-Mg[14]. Nevertheless, most of the available evidence has been derived from localized or small-scale studies, which limits its applicability to regional nutrient management and Mg fertilizer recommendation.

In parallel with efforts to understand the determinants of soil ex-Mg, a growing number of studies have highlighted the potential of Mg fertilization to alleviate ex-Mg deficiency and improve crop yield and quality. However, the effectiveness of Mg supplementation varies depending on crop system and management conditions[15]. For example, He et al.[16] demonstrated that Mg fertilization enhances nutrient absorption and yield in rice in Liaoning Province. Similarly, Mg application significantly increased wax gourd yield and seed vigor by improving carbohydrate transport to fruits and ensuring an adequate Mg supply during reproductive growth[17]. In tea cultivation, Mg supplementation has been reported to improve nitrogen use efficiency, reduces nitrogen surplus, and enhances both yield and quality[18]. Despite these advances, quantitative evidence linking regional soil ex-Mg status with yield responses across multiple crops remains limited, which constrains the formulation of site-specific Mg fertilization strategies.

Fujian Province, located in southeastern China, provides an appropriate setting for addressing these issues. As a typical subtropical agricultural region, Fujian is characterized by diverse soil types, pronounced precipitation gradients, and substantial variation in elevation[19]. These environmental heterogeneities are expected to generate marked spatial variability in soil ex-Mg and, consequently, differing crop responses to Mg fertilization. Such conditions make Fujian an ideal region in which to examine both the distribution of soil ex-Mg and the practical implications of Mg management strategies.

To address these gaps, the present study conducted a comprehensive region-wide investigation in Fujian Province: (1) characterize the spatial distribution of soil ex-Mg and identify the key environmental and edaphic factors regulating its variability based on 6833 soil samples; and (2) evaluate the responses of major crops in Fujian to Mg fertilization, thereby linking soil Mg status with crop productivity. By integrating large-scale soil survey with multi-crop field response data, this study aims to provide a scientific basis for zoning-based, soil-specific, and crop-specific Mg fertilization strategies in subtropical agricultural systems.

2 Materials and methods

2.1 Study region

Fujian Province, located in southeastern China, extends from 23°33′ to 28°20′N and 115°50′ to 120°40′E. The province covers approximately 121,400 km^2, and is characterized by a complex landscape dominated by hills, together with plains, basins, and other landforms. Elevations range from sea level to approximately 2000 m. Fujian has a typical subtropical monsoon climate, with an average annual temperature of 20.6 °C (ranging from −7 to 41.1 °C) and average annual precipitation of around 1373 mm (ranging from 800 to 2000 mm). The annual accumulated temperature above 10 °C is about 5600 °C. Owing to its diverse topography, the province exhibits pronounced regional variation in temperature and humidity. Fujian is an important agricultural region in subtropical China and is well known for the production of tea, fruits, and vegetables. The major soil types include red soils, paddy soils, and lateritic red soils, which provide favorable conditions for agricultural production. These climatic, topographic, and soil conditions make Fujian a representative agricultural region in subtropical China.

2.2 Soil survey and field experiments

2.2.1 Soil survey

To investigate the spatial distribution characteristics of soil ex-Mg concentration in Fujian Province, 6833 representative soil samples were collected from major agricultural regions across the province between 2016 and 2019.

Sampling sites were selected using a grid-based stratified random sampling approach. A 10 km × 10 km grid was superimposed on land-use and soil-type maps of Fujian Province to delineate major agricultural zones, and sampling points were randomly selected within each grid to ensure coverage of the nine major agricultural production regions and dominant soil types. This design ensured spatial representativeness across land-use types, soil classes, and climatic gradients. At each sampling site, five subsamples were collected and composited into one representative sample. These subsamples were mixed to reflect the average soil condition of each site rather than treated as independent replicates. Soil samples were collected from the 0–20 cm layer, manually mixed, and homogenized to create approximately 1 kg composite samples. The 0–20 cm layer was selected because it is the standard depth for soil fertility diagnosis and contains the main pool of readily available ex-Mg. Although perennial crops such as citrus and tea have deeper root systems, this layer remains the primary source of plant-available Mg and enables consistent comparison across cropping systems and regions. During sampling, environmental information, including geographic coordinates, elevation, precipitation, and crop type, were recorded. Samples were air-dried, ground, passed through an 80-mesh sieve, and sealed for analysis.

To evaluate potential interannual variability during the multi-year sampling period (2016–2019), the coefficient of variation (CV) of soil ex-Mg at repeatedly sampled sites was analyzed. The interannual CV was generally below 12%, indicating relatively stable Mg status. With 2019 used as the reference year, data collected from 2016–2018 were normalized to reduce year-to-year effects associated with climatic and management, thereby ensuring that the compiled dataset adequately represented the regional status of soil ex-Mg.

2.2.2 Field experiments

Eight crops were selected to evaluate the effects of Mg fertilization on yield, including tuber crops (sweet potato and potato), seed crops (peanut, soybean, and sweet corn), fruit crop (citrus), and leaf crops (cauliflower and tea). Additionally, sweet potato, peanut, citrus, and tea were assessed for nitrogen uptake efficiency (NUE) and quality responses. The field experiments were conducted from 2022 to 2023.

The experimental sites were located on the major agricultural soils of Fujian Province, including red soils and paddy soils. The preceding crops followed local rotation practices, and no specific Mg fertilizer had been applied prior to the experiments. Two treatments were established: (1) conventional fertilization (NPK) and (2) optimized Mg fertilization (NPK + Mg). Mg was supplied as magnesium sulfate heptahydrate ($MgSO_4·7H_2O$; purity ⩾ 98%; Mg content, 9.8%), which is a water-soluble Mg fertilizer commonly used in subtropical agriculture. Mg was soil-applied and incorporated as a basal fertilizer before planting. For long-duration crops, Mg was split between basal application and topdressing at the early growth-stage according to local agronomic practices. The Mg application rate was not based on a fixed NPK ratio but was determined according to: (1) the initial soil ex-Mg content at each site (Table 1), (2) local agronomic practices, and (3) crop Mg demand. Higher Mg rates were applied in severely deficient soils (ex-Mg < 60 $mg·kg^{-1}$), while moderate rates were used in moderately deficient soils (60–120 $mg·kg^{-1}$).

A randomized block design was adopted with four replicates per treatment. Each plot measured 20 m^2 (4 m × 5 m), with a 1 m buffer zone between adjacent plots to minimize edge effects. Planting density and row spacing followed local agronomic recommendations to reflect practical production conditions. Paddy fields were maintained under controlled flooding, whereas upland crops received supplementary irrigation when necessary to avoid water stress. All plots were managed according to standard local cultivation practices, including manual weed control and integrated pest management. The fertilizers applied included urea (N), superphosphate (P_2O_5), potassium chloride (K_2O), and $MgSO_4·7H_2O$. Initial soil ex-Mg concentrations (0–20 cm) at each site are presented in Table 1.

2.3 Sample measurements

2.3.1 Soil properties

Soil pH was measured in a soil-to-water suspension at a ratio of 1:2.5. Soil organic matter (SOM) was determined using the Walkley–Black dichromate oxidation method, involving $K_2Cr_2O_7$ oxidation with external heating at 170–180 °C for 5 min. CEC, available potassium (AK), exchangeable calcium (ex-Ca), and ex-Mg were extracted using a 1 $mol·L^{-1}$ $NH_4Cl–NH_4OAc$ buffer solution (pH 7.0) and quantified by ICP–OES.

2.3.2 Nitrogen uptake efficiency

NUE was calculated as the ratio of crop N uptake to the fertilizer N application rate:

$$\mathrm{NUE} = \mathrm{N_{uptake}} / \mathrm{N_{rate}} \tag{1}$$

Where N_{rate} is N the fertilizer application rate ($kg·ha^{-1}$), N_{uptake} is the crop N uptake ($kg·ha^{-1}$):

$$\mathrm{N_{uptake}} = \mathrm{N_{conc}} \times \mathrm{DW} \tag{2}$$

Where DW represents the dry weight of plant ($t·ha^{-1}$), and N_{conc} is the crop N concentration ($mg·kg^{-1}$). Crop N concentration was determined using hydrogen peroxide-sulfuric acid digestion method followed by analysis with an AA3 continuous-flow analyzer.

2.3.3 Crop yield

Crop yield was determined at maturity using standardized sampling procedures. For non-fruit-tree crops, a 1 m^2 area with uniform crop growth was randomly selected within each plot as the sampling area, and five subsamples were collected per replicate. For tuber crops, the aboveground stems and leaves were removed during harvest, and the tubers were excavated, cleaned of surface soil, and weighed. Yield was then expressed on an area basis ($t·ha^{-1}$). For seed crops, peanuts and soybeans were harvested completely, and all pods were collected after removal of impurities. In sweet corn, ears were harvested after husk removal, and cob yield was recorded and expressed as $t·ha^{-1}$. For fruit crops, five representative trees were randomly selected, and the number of fruits along with the average fruit weight were recorded. These data were then used to calculate yield per unit area ($t·ha^{-1}$). For leaf crops, tea shoots consisting of one bud and two leaves were harvested and dried. For cauliflower, the edible curd was collected after removal of the root system and weighed to calculate yield ($t·ha^{-1}$).

Table 1 Yield and soil exchangeable magnesium concentration of different crop varieties with and without magnesium fertilizer application

Category	Crop	Variety	Fertilizer dosage ($kg \cdot ha^{-1}$)		Soil ex-Mg concentration ($mg \cdot kg^{-1}$)	Yield ($t \cdot ha^{-1}$)
			$N–P_2O_5–K_2O$	Mg		
Tuber	Sweet potato	Watermelon red	165–45–195	0	129	33.8 b
				40		38.2 a
		Fushu No. 604	152–30–188	0	75	26.6 b
				45		28.1 a
		Pushu No. 12	225–90–143	0	75	30.7 b
				45		32.9 a
		Pushu No. 32	255–75–345	0	39	31.3 b
				45		36.0 a
	Potato	Minshu No. 1	180–75–135	0	39	22.9 b
				30		24.2 a
		Minshu No. 1	180–75–135	0	39	24.1 b
				30		25.6 a
Seed	Peanut	Quanhua No. 27	260–75–240	0	103	5.61 b
				60		5.94 a
	Soybean	Taimao No. 75	113–56–135	0	185	3.02 b
				30		3.53 a
		Zhexian No. 12	113–56–135	0	42	7.91 b
				40		9.26 a
	Sweet corn	Guangliang No. 27	240–120–180	0	39	12.6 b
				40		13.8 a
Fruit	Citrus	Guanxi honey pomelo	300–0–270	0	87	35.9 b
				80		43.9 a
		Aiyuan No. 28	675–195–570	0	78	32.0 b
				120		34.5 a
Leaf	Cauliflower	Changsheng	240–137–272	0	289	36.5 b
				130		38.7 a
	Tea	Wuyi cinnamon	108–48–72	0	18	6.81 b
				50		7.28 a
		Tieguanyin	360–150–225	0	12	3.81 b
				50		4.08 a

Note: Different lowercase letters indicate significant differences according to Tukey's test ($P < 0.05$)

2.3.4 Crop quality

Crop quality was evaluated using the corresponding standard methods for each crop. Sweet potato was evaluated based on starch concentration (%), determined using the iodine-potassium solution colorimetric method. Peanut quality was assessed by oil concentration (%), determined using the Soxhlet extraction method. Citrus quality was evaluated by the ratio of total soluble solids (TSS) to titratable acidity (TA), with TSS measured by refractometry and TA analyzed through sodium hydroxide titration. Tea quality was assessed based on total free amino acid concentration (%), measured using an amino acid analyzer.

2.4 Data processing methods

All statistical analyses were performed using SPSS 22. Correlation analysis was used to examine the relationships between soil ex-Mg and other soil properties, with significance assessed at $P < 0.05$ and $P < 0.01$. One-way analysis of variance followed by Tukey's test was applied for multiple comparisons. Data from field experiments were analyzed using independent-samples t-tests, with four biological replicates per treatment, consistent with the experimental design. Spatial distribution maps were generated in ArcGIS 10.2 and using kriging interpolation. Random forest analysis was performed in R (v4.4.1), and the dataset was randomly divided into training (80%) and testing (20%) subsets.

3 Results

3.1 Spatial distribution characteristics of soil ex-Mg concentration

Significant variations in soil ex-Mg concentration were observed, with an average value of 83.8 mg·kg^{-1} (Table 2). Regionally, soil ex-Mg concentrations were higher in the plains along the lower reaches of rivers, and lower in mountainous upstream regions. At the prefecture-level administrative (city-level) scale, Putian (PT) had the highest average soil ex-Mg concentration at 131.2 mg·kg^{-1}, followed by Longyan (LY) and Zhangzhou (ZZ) with 90.5 mg·kg^{-1} and 89.7 mg·kg^{-1},

Table 2 Soil exchangeable Mg concentration by province and prefecture-level administrative regions in Fujian Province

Region	Mean soil ex-Mg concentration (mg·kg^{-1})	Range (mg·kg^{-1})	Soil number	Proportion (%)
Fujian Province	83.8	≤ 30	1231	18.0
		(30–60]	1895	27.7
		(60–90]	1397	20.4
		(90–120]	1045	15.3
		> 120	1265	18.5
Fuzhou	69.1	≤ 30	21	23.9
		(30–60]	32	36.4
		(60–90]	19	21.6
		(90–120]	3	3.4
		> 120	13	14.8
Longyan	90.5	≤ 30	96	7.2
		(30–60]	309	23.3
		(60–90]	294	22.2
		(90–120]	356	26.8
		> 120	271	20.4
Nanpin	70.5	≤ 30	67	8.6
		(30–60]	288	37.1
		(60–90]	226	29.1
		(90–120]	114	14.7
		> 120	81	10.4
Ningde	59.7	≤ 30	154	40.7
		(30–60]	103	27.2
		(60–90]	54	14.3
		(90–120]	24	6.3
		> 120	43	11.4

(Continued)

Region	Mean soil ex-Mg concentration (mg·kg^{-1})	Range (mg·kg^{-1})	Soil number	Proportion (%)
Putian	131.2	≤ 30	28	5.6
		(30–60]	109	21.9
		(60–90]	92	18.5
		(90–120]	79	15.9
		> 120	190	38.2
Quanzhou	74.0	≤ 30	419	38.0
		(30–60]	304	27.6
		(60–90]	113	10.3
		(90–120]	95	8.6
		> 120	171	15.5
Sanming	68.1	≤ 30	68	9.5
		(30–60]	292	40.9
		(60–90]	224	31.4
		(90–120]	73	10.2
		> 120	57	8.0
Xiamen	62.2	≤ 30	9	19.6
		(30–60]	20	43.5
		(60–90]	8	17.4
		(90–120]	4	8.7
		> 120	5	10.9
Zhangzhou	89.7	≤ 30	369	19.4
		(30–60]	438	23.0
		(60–90]	367	19.3
		(90–120]	297	15.6
		> 120	434	22.8

respectively. Xiamen (XM) and Ningde (ND) had the relatively lower soil ex-Mg concentrations, average at 62.2 and 59.7 mg·kg^{-1}, respectively. Only 18.5% soil ex-Mg concentrations exceeding 120 mg·kg^{-1}, 81.5% soil ex-Mg concentrations were below this threshold. The detailed classification distribution of soil ex-Mg in each prefecture-level city can be found in Table 2.

3.2 Soil ex-Mg concentration across various crop planting systems

As shown in Fig. 1, soil ex-Mg concentration differed significantly among cropping systems. The vegetables cropping system had the highest soil ex-Mg concentration (104.7 mg·kg^{-1}), followed by the fruits (70.4 mg·kg^{-1}) and rice (66.5 mg·kg^{-1}) systems. By contrast, tubers and oilseeds had relatively lower soil ex-Mg concentrations, at 57.9 and 49.0 mg·kg^{-1}, respectively. The tea cropping system had the lowest soil ex-Mg concentration at 32.8 mg·kg^{-1} ($P < 0.01$).

3.3 Effects of elevation, precipitation and soil properties on soil ex-Mg concentration

Elevation and precipitation significantly affected soil ex-Mg concentration (Fig. 2(a,b)). The average soil ex-Mg concentrations were higher in low-elevation (< 300 m) and

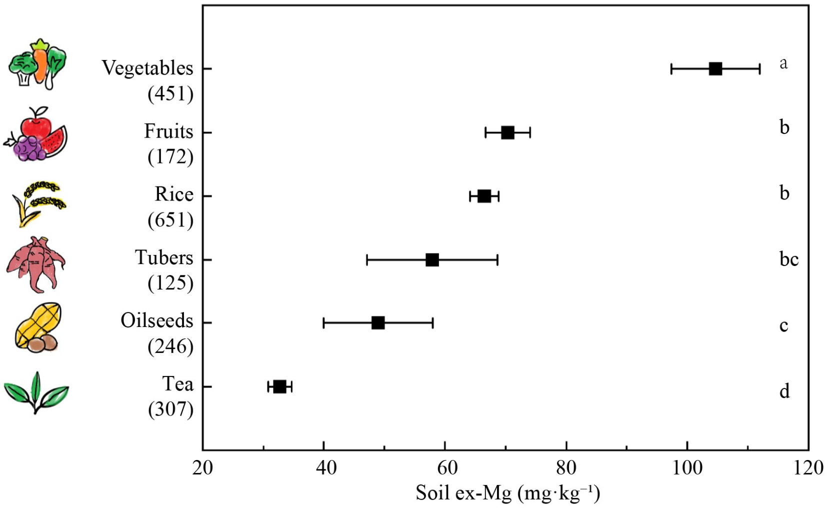


Fig. 1 Soil ex-Mg concentrations in different crop planting systems. Different lowercase letters indicate significant differences among regions according to Tukey's test ($P < 0.05$). Numbers in parentheses following each cropping system indicate the number of soil samples.

low-precipitation (< 1400 mm) regions, reaching 67.52 $mg \cdot kg^{-1}$ and 73.05 $mg \cdot kg^{-1}$, respectively) ($P < 0.01$). In contrast, lower soil ex-Mg concentrations were observed in high-elevation (> 900 m) and high-precipitation (> 1800 mm) regions, with mean value of 40.70 $mg \cdot kg^{-1}$ and 57.97 $mg \cdot kg^{-1}$, respectively ($P < 0.01$).

In addition, soil ex-Mg concentration varied significantly with soil physicochemical properties. Neutral to slightly alkaline soils (pH > 6.5) had the highest average ex-Mg concentration (135.14 $mg \cdot kg^{-1}$), which was much higher than that of strongly acidic soils (pH < 4.5, 56.64 $mg \cdot kg^{-1}$; $P < 0.01$) (Fig. 2(c)). Soil ex-Mg concentration also differed significantly among SOM. The highest average ex-Mg concentration (88.46 $mg \cdot kg^{-1}$) was observed when SOM levels of 30–45 $g \cdot kg^{-1}$. When SOM exceeded 45 $g \cdot kg^{-1}$ or ranged from 15 to 30 $g \cdot kg^{-1}$, the corresponding ex-Mg concentrations were 80.07 $mg \cdot kg^{-1}$ and 81.48 $mg \cdot kg^{-1}$, respectively, whereas the lowest value (62.54 $mg \cdot kg^{-1}$) was recorded when SOM was below 15 $g \cdot kg^{-1}$ ($P < 0.01$) (Fig. 2(d)).

Significant differences in soil ex-Mg concentration were observed across different levels of soil ex-Ca, AK, and CEC (Fig. 2(e–g)). At high levels of soil ex-Ca (> 1200 $mg \cdot kg^{-1}$), AK (> 150 $mg \cdot kg^{-1}$), and CEC (> 15 $cmol \cdot kg^{-1}$), the soil ex-Mg concentrations reached peak values of 160.23, 110.31, and 55.20 $mg \cdot kg^{-1}$, respectively. At medium levels of soil ex-Ca (400–1200 $mg \cdot kg^{-1}$), AK (50–150 $mg \cdot kg^{-1}$), and CEC (5–15 $cmol \cdot kg^{-1}$), the corresponding ex-Mg concentrations were 74.29, 79.10, and 49.04 $mg \cdot kg^{-1}$, respectively ($P < 0.01$). The lowest ex-Mg concentrations were observed at low levels of ex-Ca (< 400 $mg \cdot kg^{-1}$), AK (< 50 $mg \cdot kg^{-1}$), and CEC (< 5 $cmol \cdot kg^{-1}$), with mean value of 32.15, 66.13, and 33.20 $mg \cdot kg^{-1}$, respectively ($P < 0.01$).

3.4 Correlation between soil ex-Mg concentration and key influencing factors

Soil ex-Mg concentration exhibited significant ($P < 0.01$) negative correlations with precipitation, elevation, soil Ca/Mg ratio, and soil K/Mg ratio (Fig. 3). In contrast, it was significantly ($P < 0.01$) positively correlated with soil pH, SOM, ex-Ca, AK, and CEC. Random forest analysis further showed that soil ex-Ca concentration, precipitation, and pH were the main factors influencing soil ex-Mg concentration (Fig. 4(a,b)).

3.5 Effects of Mg fertilizer on crop yield, NUE, and quality

Mg fertilizer significantly increased crop yields across different categories (Table 1). In tuber crops, Mg fertilizer boosted sweet potato yields by 5.89%–12.92% and potato yields by 7.22%–14.94% ($P < 0.01$). In seed crops, yield increased by

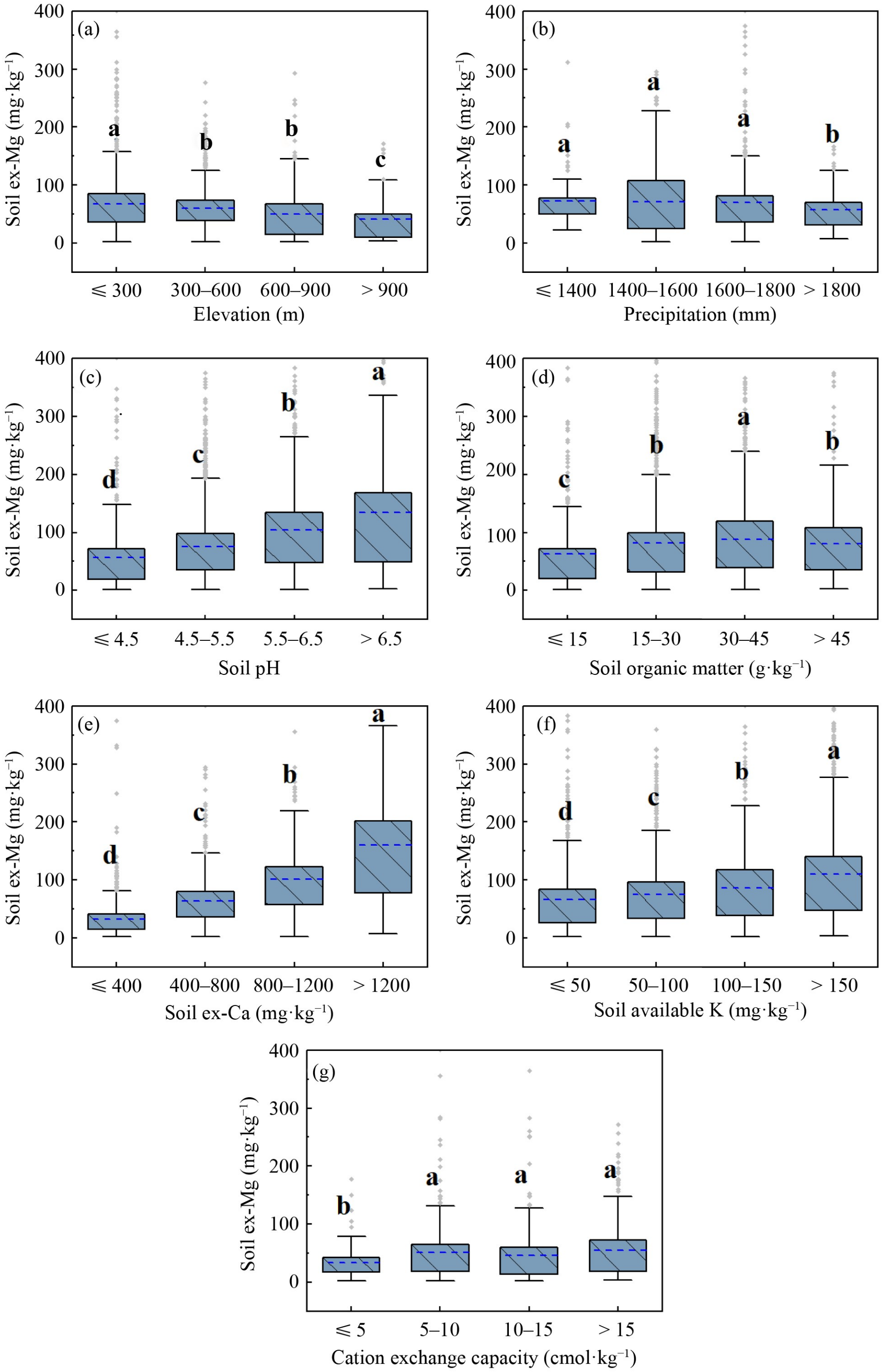


Fig. 2 Distribution of soil ex-Mg concentrations in different elevation (a), precipitation (b), soil pH (c), SOM (d), ex-Ca (e), AK (f) and CEC levels (g). The blue lines within the box represent average values, grey points indicate outliers. Different lowercase letters indicate significant differences according to Tukey’s test ($P < 0.05$).

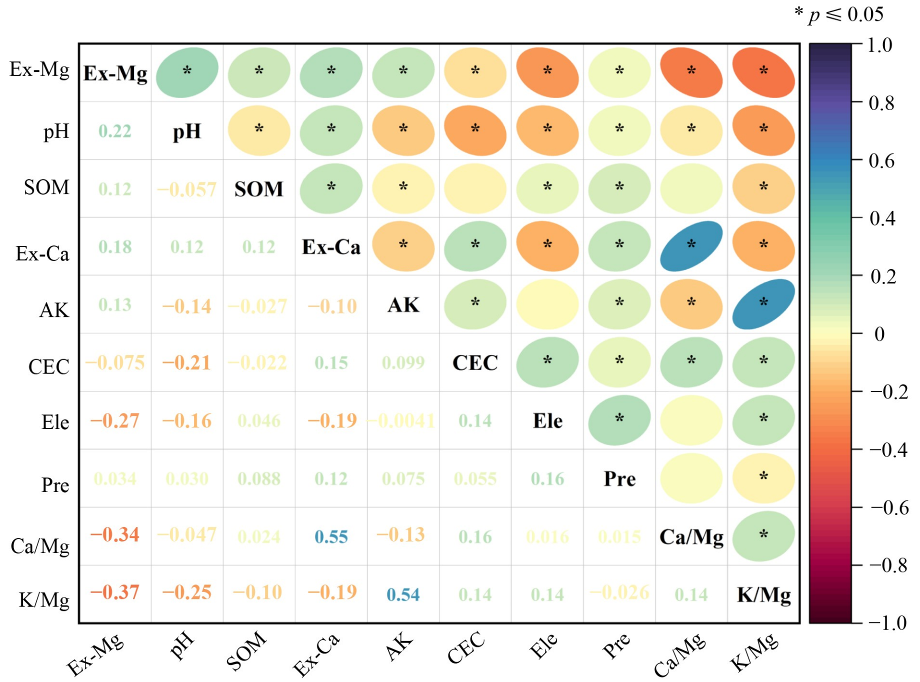


Fig. 3 Correlation matrix among soil ex-Mg concentration, pH, properties, elevation and precipitation. Ele, elevation; Pre, precipitation; Ca/Mg, the ratio of soil ex-Ca and ex-Mg; K/Mg, the ratio of soil AK and ex-Mg. The numbers were the correlation values. * indicates the corresponding values is significant ($P < 0.05$).

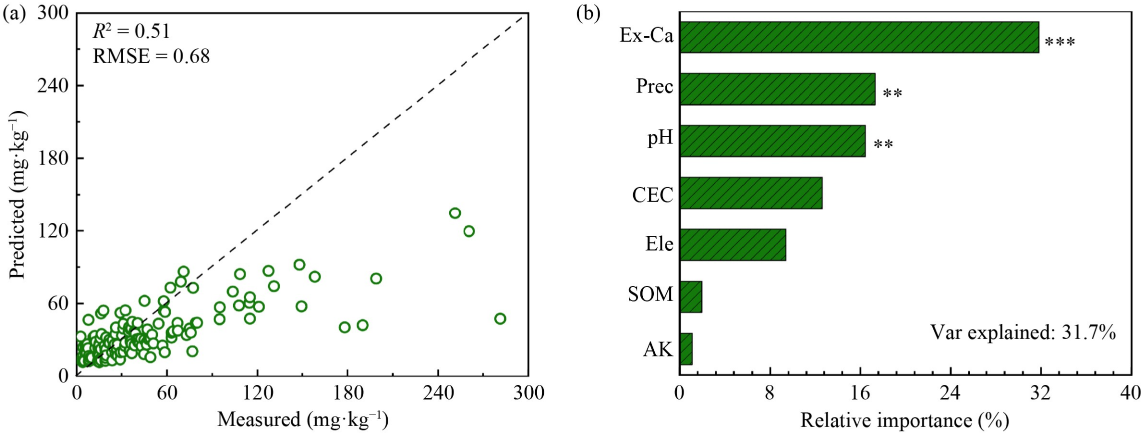


Fig. 4 Prediction of soil ex-Mg concentration based on soil properties and natural conditions using the random forest model (a), and the importance of different variables to soil ex-Mg concentration (b). R^2 and RMSE represent the coefficient of determination and root mean square error from cross-validation, respectively. ** ($P < 0.05$) and *** ($P < 0.01$) indicates the corresponding values are significant.

5.36% in peanuts, 16.86%–17.72% in soybeans, and 8.98% in sweet corn ($P < 0.01$). In fruit crops, citrus yields were significantly enhanced by 7.72%–22.19% with Mg supplementation ($P < 0.01$). Among leaf crops, cauliflower yield increased by 5.94%, whereas tea yield increased by 5.60%–7.14% ($P < 0.01$).

In addition to yield, Mg fertilizer also improved crop NUE and quality (Fig. 5). In sweet potato, NUE and starch concentration increased by 8.4% and 5.6%, respectively ($P < 0.01$; Fig. 5(a)). In peanut, Mg application increased NUE by 11.6% and oil concentration by 7.6% ($P < 0.01$; Fig. 5(b)). Citrus showed a 17.0% increase in NUE and a 10.8% increase in the TSS/TA ratio ($P < 0.01$; Fig. 5(c)). In tea, NUE increased by 28.3%, accompanied by a 7.7% increase in total free amino acid concentration ($P < 0.01$; Fig. 5(d)). Overall, Mg fertilization improved crop productivity, NUE, and quality across multiple cropping systems.

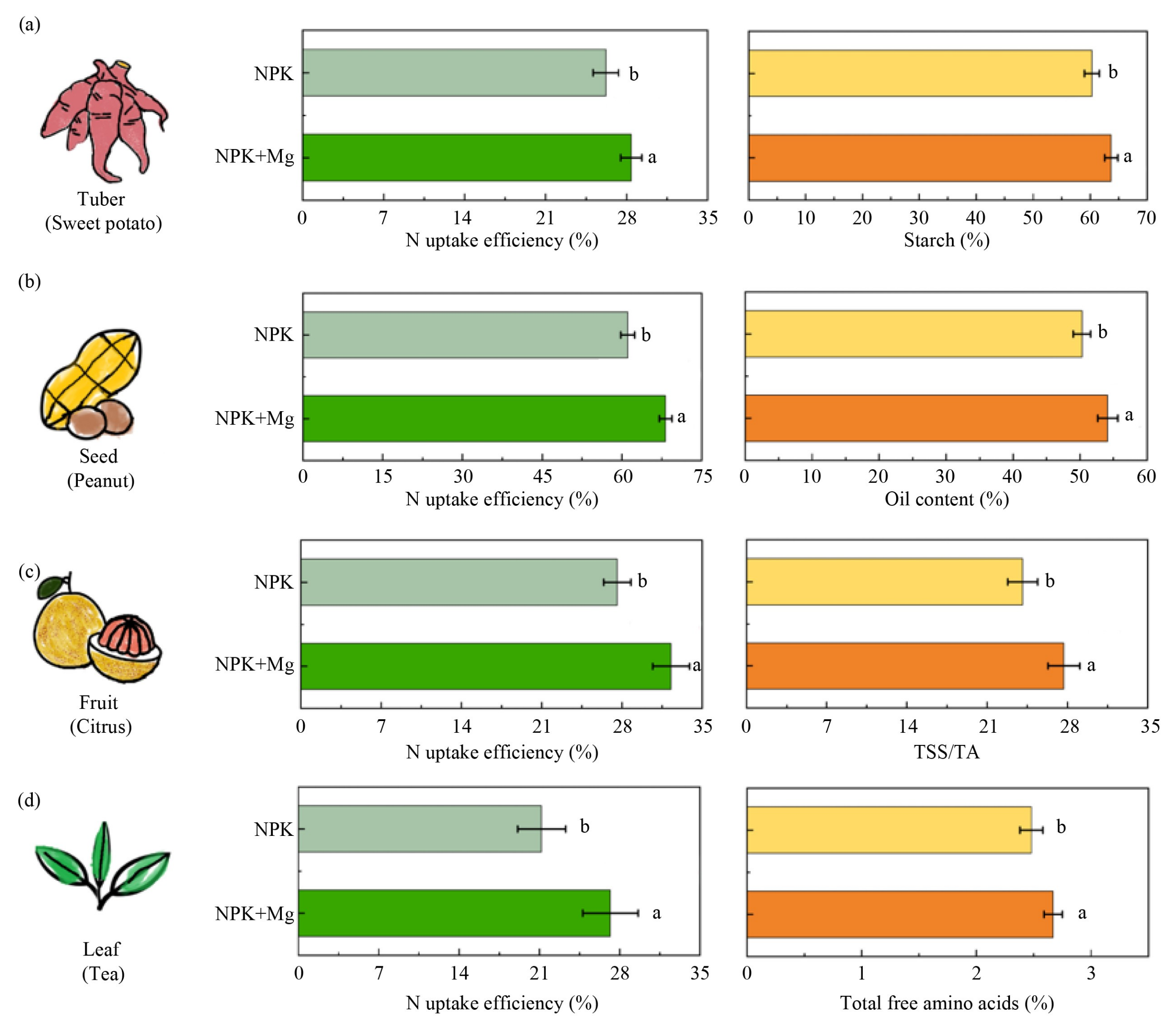


Fig. 5 N uptake efficiency and quality of sweet potato (a), peanut (b), citrus (c) and tea (d) in different nutrient management practices. Light-colored bars represent the conventional NPK treatment, and dark-colored bars represent the NPK + Mg treatment. Percentage increases indicate the NUE or quality improvement of NPK + Mg relative to NPK treatment. Error bars indicate standard deviations ($n = 4$). Different letters above bars indicate significant differences at $P < 0.05$.

4 Discussion

4.1 Spatial distribution of soil ex-Mg concentration in Fujian Province and its influencing factors

A large-scale soil survey (6833 soil samples) revealed that soil ex-Mg concentrations in Fujian Province were generally low, with an average value of 83.8 mg·kg^{-1}, and displayed marked spatial heterogeneity. Only 18.5% of samples exceeded 120 mg·kg^{-1} (Table 2), indicating that Mg deficiency is widespread in this subtropical agricultural region. This pattern is consistent with reports from parts of southwestern China[14]. Compared with previous studies that were largely based on local or site-specific investigations[20], this province-wide dataset provides a more comprehensive regional assessment and highlights the need for spatially differentiated Mg management.

The spatial pattern of soil ex-Mg was characterized by higher concentrations in downstream plains and lower concentrations in upstream mountainous areas. This distribution appears to be closely related to the combined effects of topography and climate. High precipitation is likely a key factor contributing to soil ex-Mg depletion (Fig. 2). Because Mg^{2+} is highly mobile in soil, it is readily lost through leaching and runoff in mountainous areas with abundant rainfall, especially where steep slopes promote rapid water movement[21]. In contrast, downstream plains may benefit from long-term sediment deposition, which favors the accumulation of soil nutrients, as observed in low-altitude alluvial areas[22]. The significant negative correlations of ex-Mg with both elevation and precipitation (Fig. 3) further support the importance of precipitation–topography coupling in shaping regional Mg depletion patterns, consistent with findings reported in other regions[23,24].

In addition to climatic and topographic controls, geological background and agricultural management practices likely contribute to the observed spatial heterogeneity. Downstream plains are commonly developed from alluvial or sedimentary parent materials that are relatively rich in Ca and Mg, which may provide a natural source of exchangeable base cations[25]. Moreover, these regions tend to support more intensive agricultural production, often with greater inputs of organic amendments and compound fertilizers, which may further promote soil Mg accumulation[26]. By contrast, upstream mountainous areas are dominated by highly weathered acidic soils and often receive limited Mg inputs, thereby exacerbating Mg depletion under high-rainfall conditions.

Random forest analysis identified soil pH and exchangeable Ca (ex-Ca) as key drivers of ex-Mg variability (Fig. 4). Soil acidification lowers pH and can accelerate the loss of ex-Mg through leaching[27]. When soil acidification reaches a critical threshold, the activity of Al^{3+} increases significantly[28]. Al^{3+} may further reduce Mg retention by competing for exchange sites on soil colloids[29]. From a management perspective, regulating soil acidity, for example through liming, may improve Mg retention while simultaneously alleviating Al toxicity, thereby providing a practical approach for enhancing Mg availability in acidic subtropical soils[30,31]. Although this study focuses on ex-Mg as the primary indicator of soil Mg availability, it should also be recognized that non-exchangeable and organically bound Mg pools may gradually replenish the exchangeable fraction over long-term mineral weathering, microbial activity, and pH-driven transformations.

Although Ca^{2+} and Mg^{2+} may undergo coupled leaching under high-rainfall conditions because of their similar mobility in soil solution and runoff, their interactions at the soil–colloid interface are more often characterized by competitive adsorption. Both cations compete for exchange sites, and high exchangeable Ca levels may suppress Mg retention and root uptake through adsorption competition[32]. Under intense rainfall,, however, Ca^{2+} and Mg^{2+} can also be mobilized and lost simultaneously from the soil profile, resulting in coupled depletion at the hydrological scale[33]. In acidic soils with low base saturation, enhanced Al^{3+} activity can further displaces Mg^{2+} from exchange sites, intensifying Mg depletion[34]. Together, these processes may jointly regulate Ca–Mg balance in subtropical acidic soils.

4.2 Cropping-system differences in soil ex-Mg and crop responses to Mg fertilization

Substantial variations in soil ex-Mg concentration were found across different cropping systems (Fig. 1). Beyond fertilization intensity and soil acidification, crop Mg uptake and harvest removal may also contribute to long-term differences in soil ex-Mg among cropping systems[17,35,36]. Tea plantations exhibited the lowest soil ex-Mg concentration, which may be partly attributed to repeated harvesting and relatively high annual Mg removal, coupled with insufficient Mg replenishment[37]. By contrast, vegetable systems generally showed higher soil ex-Mg concentrations, which may reflect comparatively lower Mg removal per season together with greater fertilizer and organic input intensity[27,38].

Field experiments further showed that Mg fertilization significantly increased crop yield, NUE, and crop quality (Fig. 5), consistent with previous studies highlighting the essential physiological role of Mg in subtropical cropping systems[39]. Mg is a central component of chlorophyll and plays a fundamental role in photosynthesis and biomass production[40]. It also contributes to carbohydrate transport, nitrogen metabolism, and ATP-dependent processes associated with nutrient uptake and assimilation[41–43].

Notably, positive responses to Mg fertilization were observed in several crops even when soil ex-Mg levels exceeded the commonly used sufficiency threshold of 120 $mg \cdot kg^{-1}$[44]. This threshold is largely derived from soil diagnostic criteria under moderate production conditions and may not fully capture crop-specific Mg demand, soil ionic interactions, or intensive management systems. In acidic subtropical soils, strong cation interactions, particularly among Ca^{2+}, K^{+}, and Al^{3+}, may reduce effective Mg uptake even when bulk soil ex-Mg appear adequate[45,46]. In addition, Mg availability at the root surface depends not only on the size of the exchangeable pool but also on diffusion dynamics and rhizosphere replenishment, both of which may limit Mg supply during periods of rapid crop growth. Crop-specific physiological characteristics may further explain the observed deviation from the conventional threshold concept. Tea showed a much stronger yield and quality response to Mg fertilization than cauliflower, suggesting differences in metabolic demand and root traits. Tea plants maintain active nitrogen metabolism, particularly associated with theanine biosynthesis, which relies on Mg-dependent ATP-driven enzymatic processes involved in nitrogen assimilation[47]. Under Mg-limited conditions, nitrogen assimilation efficiency and shoot quality formation may therefore be constrained. In contrast, cauliflower is a short-duration vegetable crop with rapid biomass accumulation and a relatively greater early demand for N, P, and K, which may partially buffer moderate Mg limitation[48].

Root system architecture may also contribute to this differential responsiveness. Tea develops dense fine roots in surface acidic soils and shows relatively strong tolerance to H^{+} and Al^{3+} stress, which may help maintain Mg^{2+} uptake under acidified conditions[49]. Conversely, cauliflower roots are more sensitive to Al toxicity, which can inhibit root elongation and interfere with Mg^{2+} transport, thereby reducing responsiveness to Mg fertilization unless soil acidity is simultaneously alleviated[50]. Taken together, these findings suggest that measured soil ex-Mg values do not necessarily indicate functional Mg sufficiency across all crop types. Rather than relying on a rigid universal threshold, Mg sufficiency should be interpreted in relation to crop physiological demand, soil chemical balance, and production intensity.

From a practical perspective, a detailed cost–benefit analysis was beyond the scope of this study, the observed improvements in crop yield, quality, and NUE suggest that moderate Mg fertilization is likely to be economically beneficial, especially for high-value crops grown on acidic soils. In this study, Mg was supplied as $MgSO_4 \cdot 7H_2O$. Although this fertilizer also provides sulfur, the contribution of sulfur to the observed yield responses was probably limited because conventional fertilization already included sulfur-containing inputs and sulfur deficiency was not identified as a major constraint under the study conditions.

4.3 Research limitations

Despite the comprehensive spatial survey and multi-crop field experiments, several limitations should be acknowledged. First, the spatial analysis revealed statistical associations rather than direct causal relationships, and controlled experiments are still needed to verify the underlying mechanisms. Second, the field trials were conducted over a relatively short period (2022–2023), and long-term impacts of Mg application on soil Mg dynamics and yield stability require further investigation. Third, although the observed improvements in yield and quality suggest potential economic benefits, a detailed cost–benefit analysis is still needed to support large-scale adoption. In addition, plant Mg concentrations were not measured, which limited direct evaluation of the relationship between Mg uptake and yield response. Future studies incorporating plant tissue Mg analysis would provide stronger physiological evidence for Mg fertilization effects.

5 Conclusions

Soil ex-Mg is widely deficient in the farmland soils of Fujian Province and exhibits pronounced spatial heterogeneity, with mean concentration of 83.8 mg·kg^{-1}. Soil ex-Ca, precipitation, and soil pH were identified as the dominant factors regulating its spatial variability. Field experiments further demonstrated that Mg fertilization consistently improved crop yield, NUE, and quality, and remained effective even in some soils where ex-Mg exceeded the conventional sufficiency threshold. These findings support the implementation of differentiated Mg management strategies in subtropical regions. In particular, Mg application should be prioritized in high-rainfall and strongly acidic areas, especially for Mg-demanding crops such as tea and fruit trees. Soil test-based fertilization should be adopted, with particular attention to soils with ex-Mg < 120 mg·kg^{-1}, and Mg supplementation should be integrated with soil acidity regulation where necessary. Incorporating ex-Mg into routine soil fertility diagnostics will improve the precision of nutrient management and contribute to sustainable crop production.

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Compliance with ethics guidelines

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