

## Characteristics of Soil Mineral Elements in Typical Plantations in the Karst Mountainous Area of Guizhou: Postprint

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**Date:** 2018-10-26T00:00:00+00:00

### Abstract

Elucidating the characteristics of soil mineral elements at the community level is of great significance for revealing the mechanisms of plant yield and quality formation and the laws of nutrient stoichiometric balance, and can scientifically guide the sustainable management of plantations. This study took typical plantations in the karst mountainous areas of Guizhou as the research object, classified them into metallic and non-metallic elements, and explored the content characteristics and correlations of soil mineral elements. The results showed that the content of soil mineral elements in typical plantations in this region exhibited substantial differences, and the variation amplitude of the same element differed among different tree species. Elements such as zinc, chromium, iron, titanium, aluminum, magnesium, nickel, and cobalt showed relatively consistent patterns, while calcium and strontium showed similar trends. Arsenic, selenium, and silicon had higher contents in *Eucalyptus robusta* forests, *Cupressus funebris* forests, and *Eriobotrya japonica* forests, whereas the contents of sulfur, sodium, chlorine, and other elements showed the opposite pattern. The variation patterns of different mineral elements with forest type were not completely consistent, indicating that plant root systems have different capacities for nutrient extraction and enrichment. Mineral elements exhibited a certain degree of correlation, with relationships of mutual promotion and inhibition. The correlations between different mineral elements varied, showing enhancement or inhibition effects, particularly the relationships between elements such as iron and calcium with other elements were more closely related. The interaction effects between mineral elements and their stoichiometric balance relationships are key to analyzing element characteristics and represent a scientific question worthy of in-depth study in the future. The research results are beneficial for mastering the accumulation characteristics and regulation laws of nutrient elements, and have strong theoretical and practical significance for soil nutrient management of typical plantations in this region.

## Full Text

### Preamble

DOI:10.11931/guihaia.gxzw201807021

### Characteristics of Soil Mineral Elements in Typical Plantations of Guizhou Karst Mountainous Area

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### Abstract

Clarifying the characteristics of soil mineral elements at the community level is crucial for revealing plant yield and quality formation mechanisms and nutrient stoichiometric balance patterns, and can provide scientific guidance for sustainable plantation management. This study investigated typical plantations in the karst mountainous region of Guizhou, categorizing elements into metallic and non-metallic types to explore the content characteristics and correlations of soil mineral elements. The results indicate significant variations in soil mineral element contents among typical plantations in this region, with the magnitude of variation differing for the same element across tree species. Elements such as Zn, Cr, Fe, Ti, Al, Mg, Ni, and Co showed relatively consistent patterns of variation, while Ca and Sr exhibited similar trends. As, Se, and Si contents were higher in *Eucalyptus robusta* forests, *Cupressus funebris* forests, and *Eriobotrya japonica* forests, whereas S, Na, and Cl showed the opposite pattern. The variation patterns of different mineral elements across forest types were not entirely consistent, indicating differences in nutrient extraction and enrichment capabilities among plant root systems. Mineral elements demonstrated certain degrees of correlation, exhibiting trade-off relationships with varied enhancement or inhibition effects among different element pairs, particularly for Fe and Ca which showed closer relationships with other elements. The interaction effects and stoichiometric balance relationships among mineral elements are key to analyzing elemental characteristics and represent a scientific question worthy of in-depth investigation. These findings facilitate understanding of nutrient accumulation patterns and regulation mechanisms, providing strong theoretical and practical significance for soil nutrient management of typical plantations in this region.

**Keywords:** plantation, soil, mineral element, correlation, Guizhou karst mountainous area

### Introduction

Mineral elements are among the primary factors affecting soil quality [1], playing vital roles in plant growth, physiology, and biochemical processes, and are

closely associated with the formation of plant yield, quality, and flavor compounds [2]. They serve as important indicators of soil quality and health status. Imbalanced mineral element supply exerts various impacts on plant growth and community composition, while elemental imbalance in plants relates to disrupted systemic elemental limitation equilibrium [3]. For instance, excessive nitrogen input can induce plant elemental imbalance, leading to decreased photosynthetic nitrogen use efficiency, growth retardation, and even reduced tree longevity [4, 5]. Previous research has demonstrated synergistic effects of mineral elements on peanut growth, with different elements showing interactive effects [6], indicating that mineral elements significantly influence peanut growth and physiological conditions. Silicon fertilizer application promotes scallion growth and enhances absorption of other mineral elements [7], revealing strong synergistic effects among elements. Mineral elements are directly correlated with *Camellia oleifera* development, yield, quality formation, and flavor, representing important determinant factors [8]. Appropriate P, K, Mg, Al, and Zn contents facilitate high-quality tea production [9], while rational regulation of Cu, Zn, and Fe fertilization ratios can improve Korla fragrant pear quality [10]. Therefore, systematic investigation of soil mineral element content characteristics is significant for revealing plant physiological and ecological traits and yield/quality formation mechanisms, enabling scientific guidance for healthy and sustainable plant community management.

Current research on vegetation-soil quality characteristics primarily focuses on macronutrients such as C, N, P, and K [11, 12], and biological properties [13, 14], with limited reports on medium and trace elements [15, 16]. However, medium and trace elements play irreplaceable roles in regulating plant growth, development, yield, and quality. Neglecting research on these elements is detrimental to developing integrated technical systems for quality maintenance and improvement. The above analysis demonstrates that clarifying soil mineral element characteristics of typical plantations holds strong theoretical and practical significance for scientific soil nutrient management, providing a basis for intensive land development and soil fertility improvement through land consolidation. Based on this, our study selected typical plantations in Guizhou karst mountainous areas as research objects, employing environmental mineralogy methods to investigate characteristics and variation patterns of medium and trace mineral elements in soil and reveal correlations among different elements. Through addressing these scientific questions, we aim to understand nutrient element accumulation patterns and regulation mechanisms, providing fundamental data for ecological restoration management of plantations and establishing scientific fertilization regimes.

## 1.1 Study Area Overview

The study area is located at the junction between Huajiang Town Canyon Village in Guanling County, Anshun City, and Cha'eryan Village in Beipanjiang Town, Zhenfeng County, southwestern Guizhou (105°38'48.48" E, 25°39'35.64" N). The

habitat exhibits distinct uniqueness characterized by: (1) **Hot-dry climate:** The climate type is primarily subtropical humid monsoon, with mean annual precipitation of 1,100 mm unevenly distributed across seasons, severe droughts in winter-spring and summer periods, mean annual temperature of 18.4 °C, mean annual extreme maximum temperature of 32.4 °C, mean annual extreme minimum temperature of 6.6 °C, and annual accumulated temperature of 6,542.9 °C. Winters and springs are warm and dry while summers and autumns are hot and humid, with abundant heat resources. (2) **Valley topography:** The region features deeply incised valleys with deeply buried groundwater, elevation ranging from 370-1,473 m, vertical relief of approximately 1,100 m, and typical valley climate characteristics. (3) **Developed rocky desertification:** Located in the Beipan River basin, forest coverage is less than 30%, bedrock exposure ranges 50%-80%, carbonate rocks account for 78.45%, and soils are primarily limestone-derived calcareous soils. The surface is fragmented, mostly at moderate to severe rocky desertification levels. Through comprehensive management from the 9th to 13th Five-Year Plan periods, rocky desertification has been effectively controlled and the ecological environment significantly improved.

## 1.2 Research Methods

Six typical plantation types were selected: *Eucalyptus robusta* forest, *Cupressus funebris* forest, *Eriobotrya japonica* forest, *Toona sinensis* forest, *Juglans regia* forest, and *Koelreuteria paniculata* forest (basic characteristics shown in Table 1). For each plantation type, three 10 m × 10 m plots were established. In each plot, five soil profiles were excavated using an S-shaped sampling pattern to collect 0-20 cm soil samples (or actual depth where less than 20 cm). Samples were thoroughly mixed, and approximately 1 kg was extracted using the quartering method after removing gravel and plant/animal residues, then transported to the laboratory for elemental analysis.

Soil boron (B), arsenic (As), and selenium (Se) were determined according to the *Regional Geochemical Exploration Specification* (DZ/T0167-2006). Silicon (Si), calcium (Ca), magnesium (Mg), sodium (Na), aluminum (Al), iron (Fe), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), cadmium (Cd), titanium (Ti), nickel (Ni), cobalt (Co), strontium (Sr), molybdenum (Mo), chlorine (Cl), and sulfur (S) were analyzed following the *Multi-purpose Regional Geochemical Survey Specification (1:250,000)* (DZ/T0258-2014).

## 1.3 Data Processing

Experimental data were preprocessed, calculated, and organized using Microsoft Excel 2010, plotted with Origin 8.6, and statistically analyzed using SPSS 21.0. One-way ANOVA was employed to test differences in soil mineral element indices among different plantations. Pearson correlation coefficients were used to examine correlations between soil mineral elements. Significance levels were set at  $P = 0.05$  and highly significant levels at  $P = 0.01$ .

### 2.1.1 Heavy Metal Elements

As shown in Figure 1 [Figure 1: see original paper], heavy metal element contents in soils of different plantations varied considerably, with the magnitude of variation for the same element also differing substantially among forest types. Copper content ranged 24.01–89.13  $\text{mg} \cdot \text{kg}^{-1}$ , lowest in *J. regia* forest soil and highest in *E. japonica* forest soil. Zinc ranged 148.69–209.53  $\text{mg} \cdot \text{kg}^{-1}$ , lowest in *T. sinensis* forest soil and highest in *E. robusta* forest soil. Lead concentration was highest in *C. funebris* forest soil (109.40  $\text{mg} \cdot \text{kg}^{-1}$ ) and lowest in *E. japonica* forest soil (45.67  $\text{mg} \cdot \text{kg}^{-1}$ ). Chromium showed a narrow variation range with relatively small significant differences among plantation soil types. Cadmium concentration ranged 1.33–2.65  $\text{mg} \cdot \text{kg}^{-1}$ , lowest in *E. robusta* forest soil and highest in *K. paniculata* forest soil. Manganese showed significant differences among plantation soils except between *E. robusta* and *J. regia* forests.

### 2.1.2 Non-heavy Metal Elements

Contents of non-heavy metal elements (Ca, Mg, Al, Fe, Ti, Ni, Co, Sr, Mo) in typical plantation soils are presented in Figure 2 [Figure 2: see original paper]. The results show that the same element exhibited substantial variation among different forest soils. Overall, Fe, Ti, Mg, Al, Ni, and Co showed relatively consistent variation patterns, while Ca and Sr displayed similar trends, indicating convergent variation patterns of mineral elements across different plantation soils.

### 2.2 Non-metallic Elements

The non-metallic and metalloid elements measured in this study included Na, Se, B, As, Si, Cl, and S (metalloid elements were counted as non-metallic elements). As shown in Figure 3 [Figure 3: see original paper], As, Se, and Si contents were higher in *E. robusta*, *C. funebris*, and *E. japonica* forests, whereas S, Na, and Cl showed the opposite pattern. Boron content was higher in *E. japonica*, *J. regia*, and *K. paniculata* forests. Significant differences in non-metallic element contents among different plantations reflect varying root system capabilities for nutrient extraction and enrichment.

### 2.3 Element Correlation Analysis

As shown in Table 2, mineral elements exhibited certain correlations, with varied relationships among different element pairs. Fe showed highly significant positive correlations with Cr, Pb, Ti, and Al ( $P < 0.01$ ), and highly significant negative correlations with Ca and Sr. Mn was highly significantly positively correlated with Cd, significantly positively correlated with S ( $P < 0.05$ ), and exhibited inhibitory effects on Mo, As, and Se. Ti was highly significantly positively correlated with Zn, significantly positively correlated with Al, Cr, and Pb, and highly significantly negatively correlated with Sr, Cu, and Si (all correlation coefficients  $> 0.700$ ). Ca showed negative correlations with Al, Ni, Co, Cr,

and Sr, with highly significant negative correlations with Al and Ni, significant negative correlations with Co and Cr, a significant positive correlation with B, and a highly significant positive correlation with Sr. Mg was highly significantly negatively correlated with Ca and Si, and highly significantly positively correlated with Na. Al was positively correlated with Ni, Cr, and Pb, with highly significant positive correlations with Sr and Cr, and a highly significant positive correlation with Pb (correlation coefficient = 0.829). Mo exhibited enhancement effects on Sr, Cu, and Se, with the strongest effect on Cu. Ni was only highly significantly positively correlated with Co, and significantly negatively correlated with Sr, B, and Cl. Co was highly significantly positively correlated with Cr and significantly negatively correlated with Sr. Sr showed inhibitory effects on Cr and Pb and an enhancement effect on Cu. Cu was significantly negatively correlated with Cr and highly significantly positively correlated with Si. Zn showed enhancement effects on Pb and As, with a stronger effect on As. Se was highly significantly negatively correlated with S, and Si exhibited an inhibitory effect on Cl.

### 3.1 Characteristics of Soil Mineral Elements in Different Plantations

Soil fertility comprehensively reflects fundamental soil properties and characteristics, providing essential nutrients for plant growth [17], with mineral elements being vital components. Plants absorb mineral elements from soil and accumulate them internally. Mineral elements constitute the material basis for crop growth, development, yield, and quality formation [18], and their content variations also affect plant reproductive capacity [19]. Therefore, soil fertility research based on mineral elements helps evaluate product quality formation mechanisms and guide sustainable nutrient management. Rocky desertification is a major ecological issue in karst regions [20], resulting in thin and discontinuous soil layers, slow soil formation, and severe water erosion [21]. Evaluating soil mineral elements can provide references for efficient water and soil resource utilization. Given the numerous mineral elements examined, we selected several closely related to plant growth for discussion.

In this study, the essential plant nutrient zinc ranged from 148.69 mg · kg<sup>-1</sup> in *T. sinensis* forest soil to 209.53 mg · kg<sup>-1</sup> in *E. robusta* forest soil, indicating stronger Zn dissolution and extraction capabilities of eucalyptus roots. This may relate to high litter accumulation, rapid decomposition, strong water and nutrient retention capacity, and high water transpiration in eucalyptus forests. Although *T. sinensis* is a deciduous tree, its low litter storage and strong adaptation to rocky karst habitats may result in different root extraction capabilities. From an environmental perspective, *E. robusta* forests have greater soil thickness (>20 cm) and lower rock exposure rates (10%) compared to *T. sinensis* forests (primarily utilizing fissure soils, 25% rock exposure), which also affects mineral element spatial distribution and demonstrates that soil conservation in karst plantation lands functions to regulate nutrient storage.

Boron is an essential micronutrient for plant growth and development, playing important roles in floral organ formation, pollen quantity increase, and pollination/fertilization promotion, thereby facilitating plant growth and quality formation. Among the six typical mature plantations, boron content decreased in the order: *E. japonica* forest ( $58.68 \text{ mg} \cdot \text{kg}^{-1}$ ) > *E. robusta* forest ( $56.33 \text{ mg} \cdot \text{kg}^{-1}$ ) > *J. regia* forest ( $50.83 \text{ mg} \cdot \text{kg}^{-1}$ ) > *K. paniculata* forest ( $49.75 \text{ mg} \cdot \text{kg}^{-1}$ ) > *C. funebris* forest ( $34.52 \text{ mg} \cdot \text{kg}^{-1}$ ) > *T. sinensis* forest ( $31.68 \text{ mg} \cdot \text{kg}^{-1}$ ), showing significant differences among plantation types. The superior loquat quality in this region corresponds with richer soil trace element contents, partially explaining loquat quality formation mechanisms. Although *T. sinensis* is a suitable tree species for this region, its smaller root range, fewer fibrous roots, and potentially lower root activity may result in a strategy of slow material accumulation to adapt to the special karst rocky desertification habitat.

Molybdenum's nutritional function prominently manifests in nitrogen metabolism as a component of nitrate reductase and nitrogenase, participating in rhizobial nitrogen fixation and playing special roles in reproductive organ development [22]. Mo contents in different plantation soils showed significant differences among most forest types except between *T. sinensis* and *K. paniculata* forests, with the highest content in *E. robusta* forest and lowest in *K. paniculata* forest. These results indicate that eucalyptus forests have richer Mo resources for nitrogen fixation and potentially greater Mo demand, attributable to high water transpiration rates leading to faster nutrient turnover. Additionally, *E. robusta* forests are distributed at approximately 1,200 m elevation with favorable hydrothermal conditions and abundant gaseous water resources, resulting in vigorous growth and consequently greater nutrient requirements for maintaining growth and elemental stoichiometric balance.

Chlorine is the primary mineral anion in plant cytoplasm and vacuoles; Cl deficiency in soil restricts growth, while excessive content causes phytotoxicity, with many species being chloride-sensitive. In this study, soil Cl content was highest in *K. paniculata* forest soil ( $0.34 \text{ mg} \cdot \text{kg}^{-1}$ ) and lowest in *T. sinensis* forest soil ( $0.15 \text{ mg} \cdot \text{kg}^{-1}$ ), possibly related to plant resistance levels. Furthermore, as *K. paniculata* forests intercrop with *Zanthoxylum planispinum* var. *dintanensis*, *Ipomoea batatas*, *Zea mays*, and vegetables, they experience greater agronomic interference, particularly through urea and potassium chloride fertilizer application, which may also influence Cl content.

Karst habitats are characterized by high calcium content. Soil Ca content was highest in *E. japonica* forest ( $90.95 \text{ mg} \cdot \text{kg}^{-1}$ ) and lowest in *E. robusta* forest ( $7.06 \text{ mg} \cdot \text{kg}^{-1}$ ). This difference arises because loquat is a reforestation species while eucalyptus is a natural regeneration species, experiencing different habitat stress levels and environmental background values, and exhibiting varied adaptability and absorption/transformation capacities for Ca. As *E. robusta* forests grow naturally while *E. japonica* forests experience greater human disturbance from fertilization, tillage, and harvesting, Ca content differences are significant. This demonstrates that although karst geological environments are

Ca-rich, this does not necessarily indicate abundant soil Ca content, providing theoretical references for plantation nutrient management in this region. These analyses reveal that nutrient management for plantations in central Guizhou karst mountainous areas should be quantitative and precise, representing important practical value for healthy forest management.

However, current soil mineral element research concentrates on macronutrients (N, P, K), with relatively few reports on medium and trace elements and lacking unified quality evaluation standards, making it difficult to assess element abundance or deficiency. Additionally, elements exhibit combined effects through synergism and antagonism, with different concentration combinations producing varied effects [23], representing a key scientific issue requiring attention in future soil mineral element and plant nutrition research.

### 3.2 Correlations Among Mineral Elements

Our results demonstrate that soil mineral elements in typical plantations exhibit certain correlations, indicating synergistic or trade-off relationships among different elements that function through comprehensive regulation measures. Fe showed high correlations with Ca, Al, Sr, Cr, Pb, and other elements, mostly as promotion effects, while Mn showed more inhibitory effects with other elements. These differential patterns may relate to Fe's high abundance in soil, as Fe can promote release of other elements, highlighting the importance of total Fe content. Ca and Mg also showed strong correlations with other elements: Ca with Fe, Al, Ni, Co, Sr, Cr, and B; Mg with Cu, Na, and Si, indicating trade-off characteristics among mineral elements. Specifically, Ca was highly significantly positively correlated with Fe, Sr, and Si, possibly due to synchronous activation from silicate mineral weathering. Mg showed highly significant negative correlations with Cu and Si, suggesting that high Mg content in karst areas inhibits activation of Cu and Si. Mineral elements are essential for plant growth with important physiological and ecological functions, but these functions require relatively balanced and stable conditions. Future research on elemental balance maintenance based on ecological stoichiometry [24, 25] will provide theoretical and practical foundations for nutritional function regulation.

### Conclusion

This study reveals significant differences in soil mineral element contents among different plantations, with inconsistent variation patterns across forest types indicating differential root extraction and enrichment capabilities. Elements exhibit certain correlations with trade-off relationships, particularly Fe and Ca showing closer relationships with other elements, demonstrating enhancement or inhibition effects among soil mineral elements. The interaction effects and stoichiometric balance relationships among mineral elements represent key scientific questions for future research.

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