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ORIGINAL PAPER

DISTRIBUTION OF MINERAL ELEMENTS IN THE SOIL AND IN TEA PLANTS (*CAMELLIA SINENSIS*)*

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Abstract

To understand the mineral element distribution of the soil and tea plants, we determined and analyzed the content of 16 mineral elements in the soil profile and various tea plant organs at the Yangai tea farm in Huzxi District, Guiyang City, Guizhou Province, China. The results show that the soil of the Yangai tea farm is mainly an acidic and mineral soil, which is suitable for tea plant growth. The mineral elements (i.e., Fe, S, Mo, V, and Zn) are mainly from natural sources and human activities, Se may be affected by human activities, and other mineral elements are mainly from natural sources. The tea plant has a strong ability to absorb Ca and S (especially Ca). The content of low reabsorption proficiency mineral elements (i.e., Al, Ca, Mn) in vegetative storage organs (e.g., old leaf) of the tea plant is higher than in organs with active growth and exuberant metabolism (i.e., leaf buds and flower buds). And the content of high reabsorption proficiency mineral elements (i.e., K, Mg, P, S, Mo, Cu, Ni, and Zn) in organs of the tea plant is just the opposite. In addition, the soil could provide abundant mineral elements (i.e., Mo, Se, V, Co, Cu, Ni, and Zn) for the tea plant growth, and act as the primary source of mineral elements in the tea plant. Finally, the soil within a depth of 130 cm is the mineral elements' absorption range of the tea plants in the study area. Therefore, supplies

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of the mineral elements from the deep soil layer should be a vital source of the mineral element absorption for tea plants, and considered when a fertilizer management plan for the tea garden is implemented, especially for tea plantations that are several decades old.

Keywords: mineral elements, bioconcentration factor, enrichment factor, tea plant, soil profile.

INTRODUCTION

Mineral elements play a vital role in the health of plants and their consumers. A mineral element is defined as a chemical element (except for C, H, and O) that is usually absorbed from the soil and used by the plant as a building block, and which can be retained in the ash from incineration of the plant organism (except for N). Liebig's theory of mineral nutrition clarifies that the essence of plant absorption of nutrients is to obtain mineral elements, and plants can grow healthily when acquiring the necessary nutrients (Bai 2019). Mineral nutrition plays a crucial role in the plant growth, development, and reproduction (Mo et al. 2021). The beneficial effect of adding mineral elements (e.g., plant ash or lime) to soils in order to improve plant growth has been known in agriculture for more than 2,000 years (Marschner 2012). Mineral elements have significant physiological functions (i.e., acting as cofactors for metabolic enzymes, oxygen transport, DNA synthesis and repair, cell division, antioxidation, immune function, etc.) that are responsive to chemical exposure (Smith, Lucas 2020).

The content of mineral elements in the tea leaves plays a vital role in the healthy growth of the tea plant and resulting tea quality. Both the quality of tea leaves and the positive health effects of tea infusion depend on the content of polyphenolic substances and mineral elements in tea leaves (Tolrà et al. 2020). The tea producers and consumers are concerned about the accumulation of mineral elements (Zhang et al. 2018). When a mineral element deficiency or excess occurs, it will bring adverse health consequences to the plant. Namely, an insufficient intake leads to some lesions or dysfunction, and the mineral element in question is needed if its supplementation up to the physiological level can prevent or repair the damage (Guardia, Garrigues 2015). Most minerals could significantly promote healthy growth and play an important role in biochemical functions and enzymatic systems even at the lowest levels (Bhat et al. 2010). The mineral elements (i.e., Al, Ba, Cd, Pb, Co, Cu, Cr, Sn, Ag, Tl, V, and Zn) in the tea samples exceed the daily intake, which corresponds to 0.2 to 2 % of the amount of absorbed micronutrients necessary for a healthy balance (Schunk et al. 2016). When the tea plant grows with P deficiency or excess, the plant's anabolism and catabolism of metabolites are affected, its antioxidant activity is weakened, the content of the mineral element (e.g., Cu, Zn, and S) in the tea leaves changes, and the synthesis of flavonoids in the tea leaves is reduced (Ding et al. 2017).

The soil depth (especially the deep soil layer) plays a vital role in absorbing water and mineral elements by deep-rooted plants or trees. Approximately 2/3 of the nutrients of deep-rooted plants and trees occur at a depth of 2 m in the surface soil layer, although there are differences among individual soil types (Yost, Hartemink 2020). And the storage and availability of nutrients are affected by soil depth, which is very important for agricultural production and plant growth (Yost, Hartemink 2019). Deforestation, which affects depth distributions of carbon inputs from roots, may also affect the net carbon storage in soil (Nepstad et al. 1994). Deep roots provide vital functions (i.e., nutrient and water uptake) for individual plants and influence soil pedogenesis and carbon storage (Maeght et al. 2013).

Previous studies focused on the distribution of mineral elements in various organs of the tea plant, and few dealt with the effect of the different soil layers (especially the deep soil layer) on the absorption of mineral elements in tea plants. Because tea is one of the three major beverages of the world, it is vital to study the content of mineral elements in the tea plant. Sha and Zheng (1996) found that the content of 19 mineral elements in some organs (i.e., flower buds, leaves, and fine roots) of the tea plant were higher than in other organs (i.e., seeds, twigs, backbone branches, primary axis, trunk, main root, lateral root). Through the study on the distribution of Pb in 10-years-old tea plants in Longjing 43, Han et al. (2009) found that the Pb content in absorbing roots was the highest, followed by productive branches, lateral branches, and old leaves, and the Pb content of tea seeds and young shoots was lower. After analyzing the distribution of Fe and Mg content in four tea varieties, Shan et al. (2017) concluded that Fe mainly accumulated in tea roots and stems, the Mg content of old leaves was the highest, and differences in the distribution of minerals in other organs is not significant.

The content of 16 mineral elements (e.g., Al, Ca, Fe, K, Mg, Na, P, S, Mn, Mo, Se, V, Co, Cu, Ni, and Zn) in different organs of the tea plant and in the soil profile at the Yangai tea farm of Guiyang City, China, was determined and analyzed to understand the effect of the soil depths on the distribution, absorption, and transport of mineral elements in the tea plant.

MATERIALS AND METHODS

Study area

The Yangai tea farm was started in 1952. It is located in Huaxi District, Guiyang City, Guizhou Province, China (N26°23′19″ E106°31′27″). It lies in the southwest suburb of Guiyang City, which is 40 km away from the downtown of Guiyang City (Gong, 2010). The Yangai tea farm site is on a hilly platform of the central Guizhou Province. It has some unique characteristics (i.e., the gentle slope of an Alpine-like platform, cloudy and moist air in early spring). The altitude in the study area ranges from 1200 m to 1400 m, averaging 1300 m. The annual rainfall is within the range of 1200 - 1300 mm. The length of the frost-free season is 247 days. The mean annual temperature is 14.2°C, and the temperature difference between day and night ranges from 3°C to 13°C. The environment and weather conditions are suitable for tea plant growth, promoting the formation of tender and excellent quality tea buds. The variety of tea plants grown on the Yangai tea farm is a population variety of early bud and middle leaf types of the Shilixiang in northern Yunnan Province of China, which germinates earlier and has denser hairs on the back of leaves than the local varieties (Gong 2010).

Sampling

In mid-August 2018, we collected two representative soil profiles and their corresponding tea plants (YA-1 and YA-2) – Table 1 at the Yangai tea farm in the Guiyang City, in China. A total of 55 samples were collected,

Table 1

Soil profile characteristics in the Yangai tea farm of Guiyang City

Sample profile	Sample depth (cm)	Sample characteristic
YA-1	0~10	The soil is grayish brown and contains many tea plant roots. The main root diameters of the tea plant range from 40 to 58 mm, and most root diameters are about 40 mm. Additionally, this layer of the soil contains a large number of small roots and absorbing roots.
	10~20	The soil is dark brown and contains many tea plant roots. The root diameters of the tea plant range from 34 to 48 mm, and most root diameters are about 34 mm. Additionally, this layer of the soil contains a large number of small roots and absorbing roots.
	20~30	The soil is dark brown and contains many tea plant roots. The root diameters of the tea plant range from 32 to 38 mm, and most root diameters are about 32 mm. Additionally, this layer of the soil contains a few small roots and absorbing roots.
	30~40	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 30 to 34 mm, and most root diameters are about 30 mm.
	40~50	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 22 to 30 mm, and most root diameters are about 22 mm.
	50~60	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 16 to 26 mm, and most root diameters are about 16 mm.
	60~70	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 11 to 20 mm, and most root diameters are about 11 mm.
	70~80	The soil is brownish yellow and contains a small number of tea plant roots with a root diameter of about 16 mm.

cont. Table 1

Sample profile	Sample depth (cm)	Sample characteristic
YA-1	80~90	The soil is brownish yellow and contains a small number of tea plant roots with a root diameter of about 13 mm.
	90~110	The soil is brownish yellow and contains a small number of tea plant roots with a root diameter of about 10 mm.
	110~130	The soil is light brown and contains many tea plant roots with a root diameter ranging from 2 to 10 mm.
	130~140	A hard iron layer is a brick-red-black hard layer containing abundant Fe content and a small amount of tea plant roots. And their root diameter ranges from 2 to 5 mm.
YA-2	0~20	The soil is dark brown and contains many tea plant roots. The root diameters of the tea plant range from 22 to 36 mm, and most root diameters are about 22 mm. Additionally, this layer of the soil contains a large number of small roots and absorbing roots.
	20~40	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 20 to 26 mm, and most root diameters are about 20 mm. Additionally, this layer of the soil contains a large number of small roots and absorbing roots.
	40~60	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 18 to 22 mm, and most root diameters are about 18 mm.
	60~80	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 16 to 20 mm, and most root diameters are about 16 mm.
	80~100	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 14 to 18 mm, and most root diameters are about 14 mm.
	100~120	The soil is light brown and contains many tea plant roots. The root diameters of the tea plant range from 10 to 15 mm, and most root diameters are about 10 mm.
	120~122	The soil is light brown, located about 2 cm on the surface of the iron layer at the bottom, and contains more absorbing roots.
	122~130	A hard iron layer attached more absorbing roots to its surface, and a small amount of tea plant root passes through.

including 20 soil specimens and 35 plant samples. The plant samples were collected from different organs of one tea plant (i.e., trunk xylem, root xylem, trunk phloem, root phloem, flower buds, old leaves, tertiary branches, secondary branches, trunks, and roots at different depths). In the soil profile of YA-1, pairs of soil and tea plant root samples were gathered at each 10 cm depths to the maximum of 90 cm, respectively. And the sampling intervals were increased to each 20 cm within a depth range of 90 to 130 cm. Finally, a pair of soil and tea plant roots were collected from the hard iron layer (i.e., a brick-red-black hard layer containing abundant Fe content) within a depth range from 130 cm to 140 cm. In the soil profile of YA-2, pairs of soil and tea plant root samples were gathered at each 20 cm depth to the maximum of 120 cm, respectively. A soil sample was collected from the surface of the hard iron layer within a depth ranging from 120 cm to 122 cm. And a pair of soil and tea plant root samples were gathered at the hard iron layer, within a soil depth range of 122 cm to 130 cm. The weight of each soil sample was approximately 1000 g.

Soil sample preparation and mineral element determination

After removing the impurities (e.g., gravel, plant residue, etc.), the soil sample was halved by dichotomy and then dried in a thermostatic air-blower--driven drying closet at 30°C. Then, each dry soil sample was passed through a 10-mesh nylon sieve. 10.00 g of Each soil sample was weighed prior to a soil pH measurement with a pH meter (SX620 type, Instrument Factory of Shanghai Sanxin, Shanghai, China) at a soil-water ratio of 1 to 2.5. And the soil organic matter (SOM) content of soil samples was determined by KCr_2O_7 oxidation coupled with a volumetric technique (NY/T 85-1988). Finally, the mineral element content of the soil samples was determined with an ICP-AES (America, Agilent VISTA) and an ICP-MS (America, Agilent 7700x) in an accredited laboratory, ALS Minerals – ALS Chemex (Guangzhou) Co. Ltd.

The sample determination procedure for the soil samples was as follows (Peng et al. 2018*a*,*b*): approximately 100 g of each dry soil sample were gently disaggregated with a rubber hammer and sieved through an 80-mesh nylon sieve. These sieved samples were separated into two parts for analysis and storage. Two test samples (0.25 g and 0.50 g) were weighed from each prepared soil sample. The first sample (0.25 g) was digested with a concentrated acid mixture of $HClO_4$, HNO_3, HCl, and HF and diluted to a constant volume with dilute HCl. Another sample (0.50 g) was digested with aqua regia in a graphite heating block. After cooling, the digested solution was diluted to a steady volume with deionized water. Finally, the mineral element content of the volume solution was respectively determined by ICP-AES and ICP-MS. According to the actual characteristics of the samples, the digestion effect, and interelement spectral interferences, the integrated value was the final test result.

Plant sample preparation and mineral element determination

Each plant sample was rinsed with deionized water approximately two times after washing with high-pressure water. It was dried in a thermostatic air-blower-driven drying closet at 60°C for 30 min and then at 30°C. The dried plant samples were pared down with a ceramic knife and then ground with an agate mortar passing through a 100-mesh nylon sieve. Additionally, the sample determination procedure for the soil sample was as follows (Peng et al. 2018*a*,*b*): Each prepared dry specimen (1.0 g) was cold-digested for approximately eight hours in HNO_3. Then, it was heated for three hours in a graphite heating block. It was subsequently cooled and brought up to a constant volume with dilute HCl. Finally, the mineral element content of the plant samples was determined by ICP-AES and ICP-MS in an accredited laboratory, ALS Minerals – ALS Chemex (Guangzhou) Co. Ltd. The final analytical results were considered for inter-element spectral interferences, the actual characteristics of the samples, and the digestion effect.

Data processing and statistical analysis

The enrichment factor (EF) is a relative abundance of a mineral element to distinguish the elemental source, that is, whether the source is anthropogenic or natural (Peng et al. 2017*a*, 2018*b*, 2021, Zhang et al. 2014). The enrichment factor is calculated by Eq. (1).

$$\mathrm{EF} = \frac{\left(\frac{\mathrm{Me}}{\mathrm{Al}}\right)_{\mathrm{soil}}}{\left(\frac{\mathrm{Me}}{\mathrm{Al}}\right)_{\mathrm{crust}}} \tag{1}$$

The neutralization formula $(\mathrm{Me/Al})_{\mathrm{soil}}$ and $(\mathrm{Me/Al})_{\mathrm{crust}}$ is the ratio of the content of a mineral element to Al in the soil and crust (Taylor 1964), respectively.

The bioconcentration factor (BCF) is the ratio of the content of an element in a plant to that of its growth media, which is mainly used to evaluate an element enrichment ability of the plant (Peng et al. 2017a, 2018*a*,*b*). It was calculated by Eq. (2).

$$\mathrm{BCF} = \frac{C_p}{C_s} \tag{2}$$

C_p represents an element content of the plan. And C_s represents an element content of the plant growth soil, which is the average content of the element in all soil samples in this study.

Statistical processing of the data and analysis were performed with Excel and SPSS 19.0. Additionally, the analytical results of this study were tested for normal distribution by the Shapiro-Wilk method to choose the proper statistical tools (Peng et al. 2018*a*). The level of $P<0.05$ for several variables represnted a significant difference, and thus, nonparametric tests (of one-sample Kolmogorov-Smirnov tests) were used (Peng et al. 2018*b*). Bar chart diagrams were plotted with Excel and improved picture quality was achieved with CorelDraw X6 software.

RESULTS AND DISCUSSION

Characteristics of SOM and soil pH distribution in soil profile

The soil of the Yangai tea farm is mainly acidic soil and mineral soil. It is suitable for the growth of the tea plant. The SOM in the soil section of the Yangai tea farm ranges from 0.04 to 8.08 g kg^{-1}, with an average value of 2.72 g kg^{-1} (Table 2), indicating that the soil is mineral one. And the SOM content demonstrates a decreasing trend with increasing soil depth (Figure 1). The surface soil layer in the Yangai tea farm is mainly gray-brown or dark brown soil, and other deep soil layers are primarily light brown soil (Table 1). This reason might be the influence of soil humus and soil organic matter on the surface soil. Then, the soil pH in the soil profile of the Yangai tea farm ranges from 4.61 to 5.81, with an average value of 5.18 (Table 2), indicating the soil is mainly acidic. The soil pH is suitable for the growth of the tea plant. The soil pH of the soil profile is less than 5.0 within the soil depths of 40 cm or 50 cm, which corresponds to strongly acidic soil. And the soil pH value shows an increasing trend with increasing soil depth (Figure 1). In addition, the taproot diameter and root biomass of the tea plant decrease with increasing soil depth. In the initial stage of tea plantation, most acidification occurred in the soil around the tea plant root (Song, Liu 1990). The intensive interaction between the plant root exudation and rhizosphere microorganisms could affect physicochemical properties

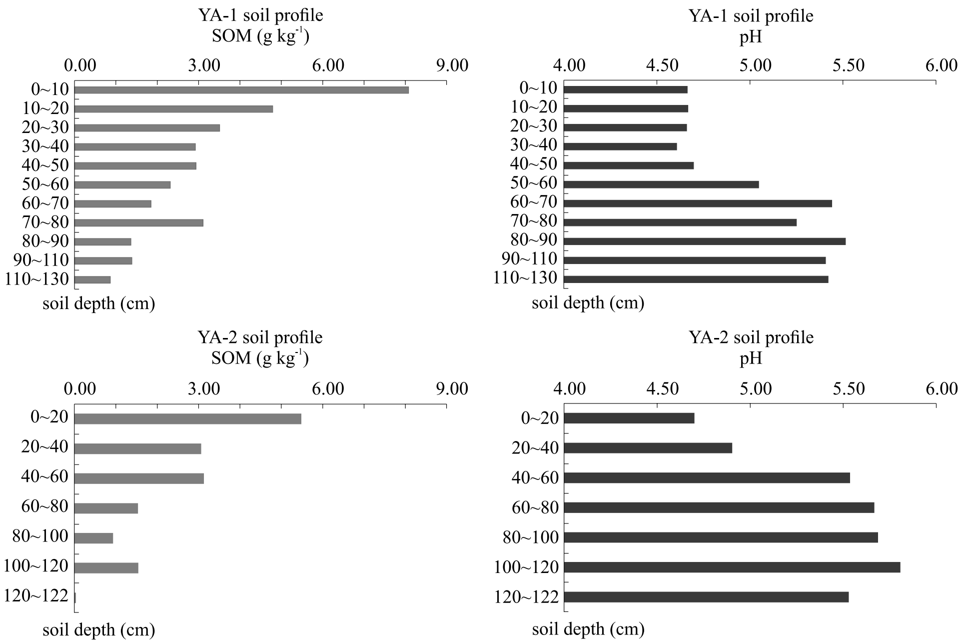


Fig. 1. Value of SOM and soil pH in the soil profile in the Yangai tea farm of Guiyang City

Table 2

Content of mineral elements in the soil profile and the tea plant in the Yangai tea farm of Guiyang City

Content of mineral elements in:		Al	Ca	Fe	K	Mg	Na	P	S	Mn	Mo	Se	V	Co	Cu	Ni	Zn	SOM	pH
Soil profile	minimum	64 400	100	70 100	6 500	1 900	300	510	100	211.00	2.56	1.00	112.00	17.10	53.90	33.90	138.00	0.04	4.61
	maximum	146 500	900	371 000	18 200	7 000	700	1080	1100	7 500.00	5.24	1.00	244.00	90.30	95.10	98.80	230.00	8.08	5.81
	average	123 245.00	425.00	134 095.00	14 935.00	5 775.00	660.00	655.00	595.00	784.15	4.25	1.00	211.55	27.66	77.13	73.70	183.30	2.72	5.18
	within soil depth of 40 cm	82 300	41 500	56 300	20 900	23 300	2 3600	567	260	401.83	3.79	1.00	201.17	18.90	62.25	61.15	155.67	4.64	4.70
	within soil depth of 40~80 cm	114 833	317	82 317	13 883	5 483	700	638	833	269.83	4.62	1.00	221.33	22.73	82.73	78.87	191.00	2.48	5.27
	under soil depth of 80 cm	127 583	617	132 500	15 533	6 100	650	795	850	653.50	4.60	1.00	232.00	32.07	90.12	89.10	212.33	1.02	5.56
	hard iron layer	140 333	433	135 500	16 967	6 600	700	550	250	3 866.00	3.46	1.00	152.00	55.45	66.00	49.65	156.00		
The continental crust		84 200	150	290 000	10 200	3 200	450	1050	150	950.00	1.50	0.05	135.00	25.00	55.00	75.00	70.00		
The tea plant	minimum	250	800	13	1 400	250	20	160	290	59.8	0.01	0.02	0.1	0.092	1.03	0.57	4.6		
	maximum	9 500	12 700	4 980	12 200	4 390	1400	2790	3180	1 890	0.11	0.6	4.3	4.18	154	114	101		
	average	1 424.00	2 957.14	577.69	4 397.14	1 325.71	261.43	596.86	1 154.86	419.24	0.02	0.12	0.54	0.76	16.01	12.58	21.75		

Note: Except the unit of soil organic matter (SOM) and soil pH, which are expressed in g kg^{-1} and a dimensionless parameter, respectively, other parameters are given in mg kg^{-1}.

(e.g., soil acidity, soil moisture, and soil nutrient status) of the rhizosphere soil (Huang 2004). With the expansion of a tea plantation, fallen leaves begin to play a key role in soil acidification (Song, Liu 1990). Plant roots and leaves producing strong organic acids can also acidize the rhizosphere (Peng et al. 2018*a*). Without Al-toxicity, the concentration of isocitrate, citrate, and malate in the root and leaf at pH 2.5 - 3.0 rose with increasing pH, then declined or remained unchanged with a further increase of pH (Yang et al. 2020). These findings indicate that the soil of the upper soil profile is greatly affected by the SOM content and the secretion of organic acids by tea plant roots (especially the absorbing roots).

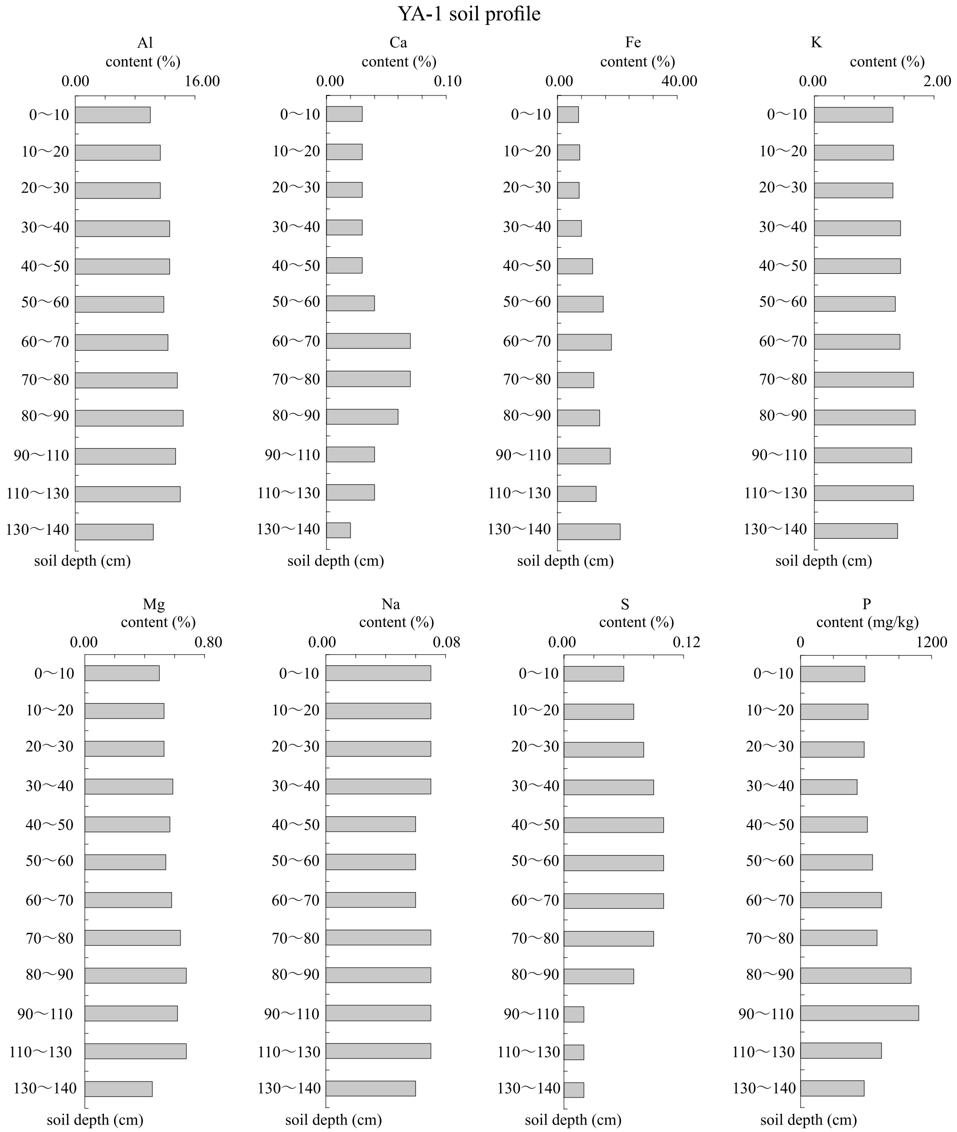
Characteristics of mineral element distribution in soil profile

The average content order of all mineral elements in the soil in the Yangai tea farm is Fe>Al>K>Mg>Mn>Na>P>S>Ca>V>Zn>Cu>Ni>Co>Mo>Se (Table 2). The soil Se content of the soil profile in the Yangai tea farm is about 1 mg kg^{-1} (Figure 2). The content of Al, Ca, Fe, K, Mg, Na, P, S, Mn, Mo, V, Co, Cu, Ni and Zn, respectively, ranges from 6.44 to 14.65%, 0.01 to 0.09%, 7.01 to 37.10%, 0.65 to 1.82%, 0.19 to 0.70%, 0.03 to 0.07%, 510 to 1080 mg kg^{-1}, 0.01 to 0.11%, 211 to 7500 mg kg^{-1}, 2.56 to 5.24 mg kg^{-1}, 112 to 244 mg kg^{-1}, 17.1 to 90.3 mg kg^{-1}, 53.9 to 95.1 mg kg^{-1}, 33.9 to 98.8 mg kg^{-1}, 138 to 230 mg kg^{-1}. And their average content is 12.32%, 0.04%, 13.41%, 1.49%, 0.58%, 0.07%, 655 mg kg^{-1}, 0.06%, 784.15 mg kg^{-1}, 4.25 mg kg^{-1}, 211.55 mg kg^{-1}, 27.66 mg kg^{-1}, 77.13 mg kg^{-1}, 73.70 mg kg^{-1}, 183.30 mg kg^{-1}, respectively.

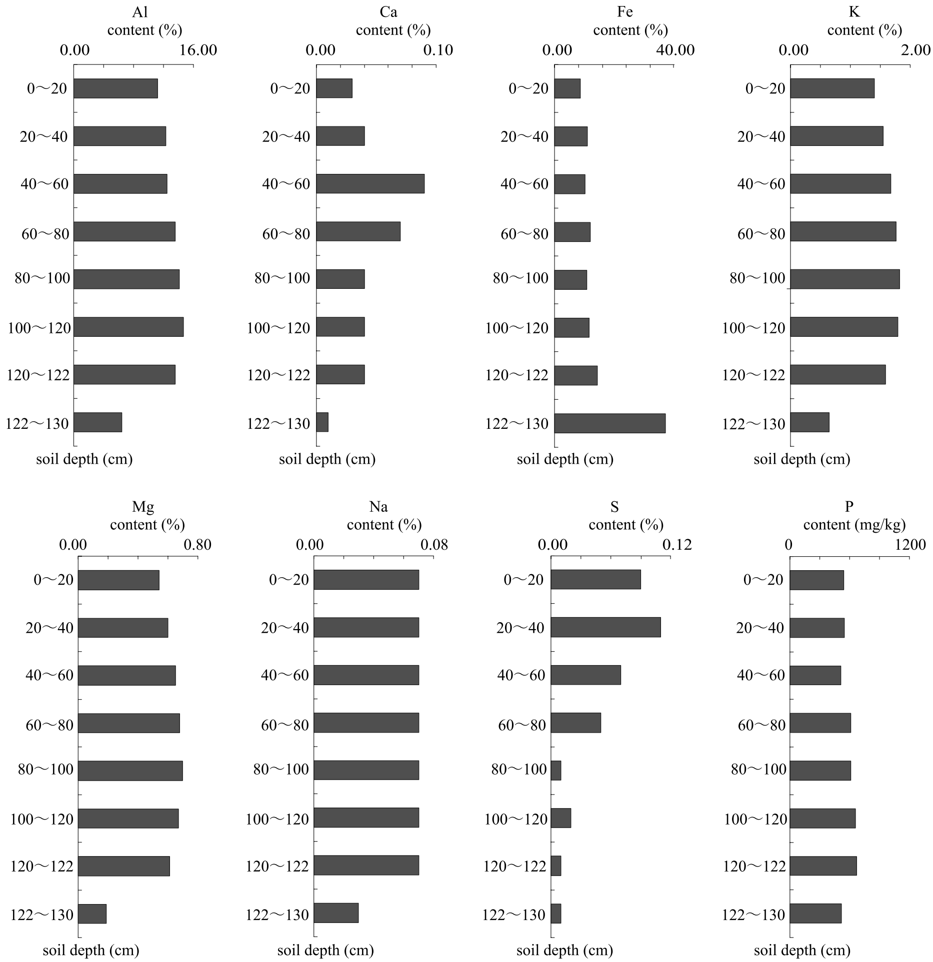
The content of the soil mineral elements (i.e., Al, Ca, K, Mg, Na, S, P, V, Mo, Cu, Ni, and Zn) in the Yangai tea farm shows a gradual increase and then a decrease with increasing soil depth (Figure 2). It might result from agronomic measures (i.e., fertilization), rainwater infiltration, and the absorption of tea plant growth. The Co content rises with increasing soil depth. And the content of Fe and Mn shows a decrease and then an increase with increasing soil depth. These trends might result from the absorption of nutrients by tea plants and the soil environment (i.e., soil pH). The availability and mobility of Co, Fe, and Mn decrease with an increasing soil pH value, at pH 4 - 8 (Weil, Brady 2016, Xu 2019). However, the Se content does not change significantly with increasing soil depth.

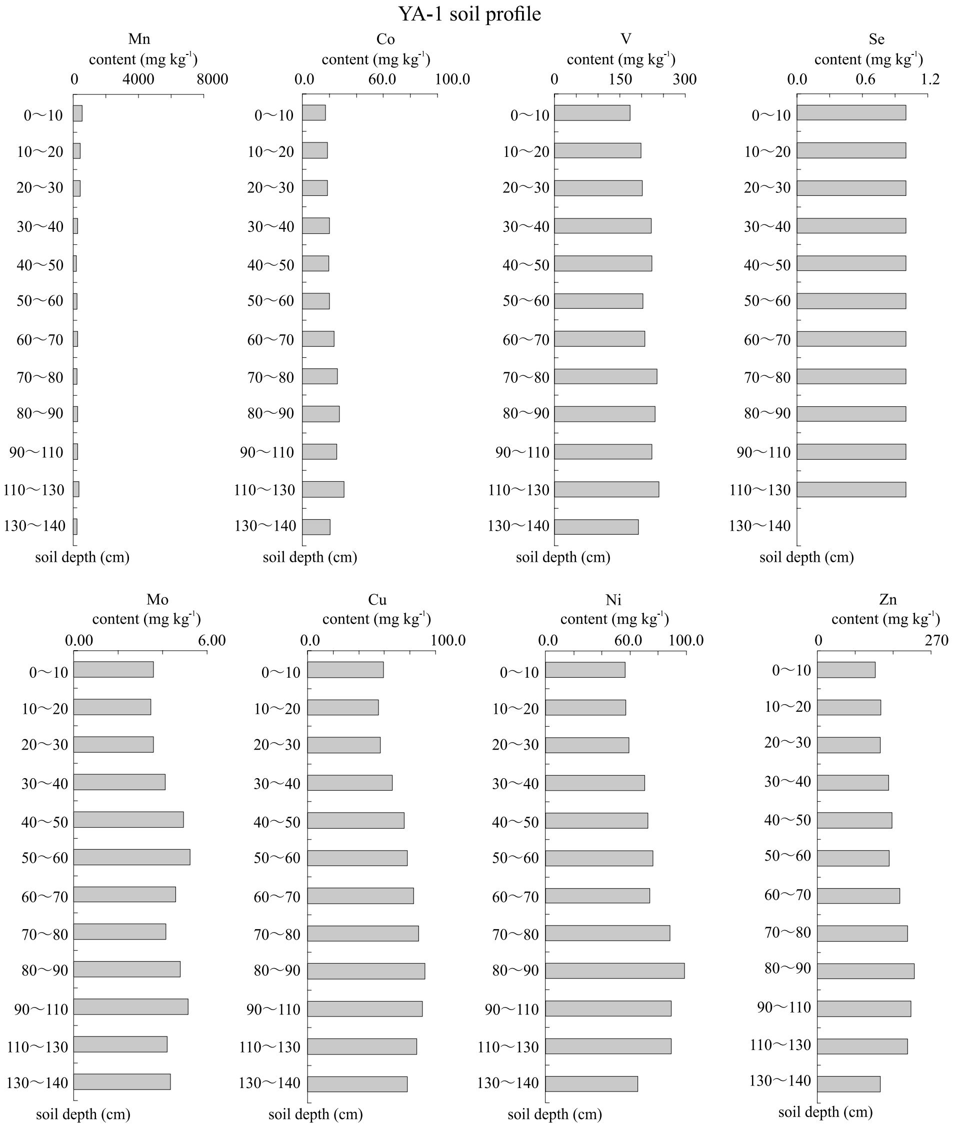
Distribution characteristics of mineral elements in tea plant

The average content of mineral elements in tea plant organs is in the following order: K>Ca>Al>Mg>S>P>Fe>Mn>Na>Zn>Cu>Ni>Co>V>Se>Mo (Table 2). It is similar to the result of Sha and Zheng (1996). The average content of Al, Ca, Fe, K, Mg, Na, P, S, Mn, Mo, Se, V, Co, Cu, Ni and Zn is respectively 1424, 2957.14, 577.69, 4397.14, 1325.71, 261.43, 596.86, 1154.86, 419.24, 0.03, 0.12, 0.60, 0.763, 16.01, 12.58, and 21.75 mg kg^{-1}. It ranges from 250 to 9500, 800 to 12 700, 13 to 4980, 1400 to 12 200, 250


YA-1 soil profile
Al
content (%)
Ca
content (%)
Fe
content (%)
K
content (%)
Mg
content (%)
Na
content (%)
S
content (%)
P
content (mg/kg)
soil depth (cm)

YA-2 soil profile




YA-1 soil profile
Mn
content (mg kg-1)
0 4000 8000
Co
content (mg kg-1)
0.0 60.0 100.0
V
content (mg kg-1)
0 150 300
Se
content (mg kg-1)
0.0 0.6 1.2
Mo
content (mg kg-1)
0.00 6.00
Cu
content (mg kg-1)
0.0 100.0
Ni
content (mg kg-1)
0.0 60.0 100.0
Zn
content (mg kg-1)
0 270
0～10
10～20
20～30
30～40
40～50
50～60
60～70
70～80
80～90
90～110
110～130
130～140
soil depth (cm)

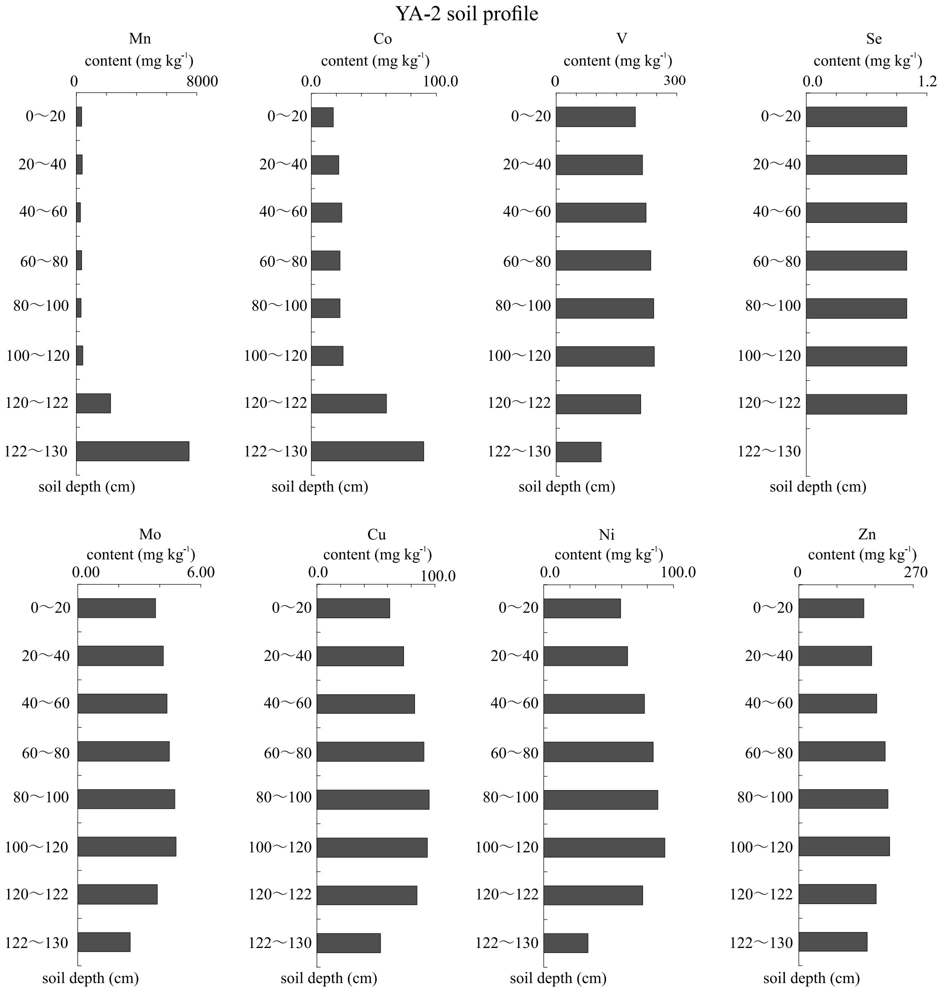


Fig. 2. Vertical distribution characteristics of mineral elements in the soil profile in the Yangai tea farm of Guiyang City

to 4390, 20 to 1400, 160 to 2790, 290 to 3180, 59.8 to 1890.0, 0.01 to 0.11, 0.02 to 0.60, 0.1 to 4.3, 0.092 to 4.180, 1.03 to 154.00, 0.57 to 114.00, and 4.60 to 101.0 mg kg^{-1}, respectively (Table 2).

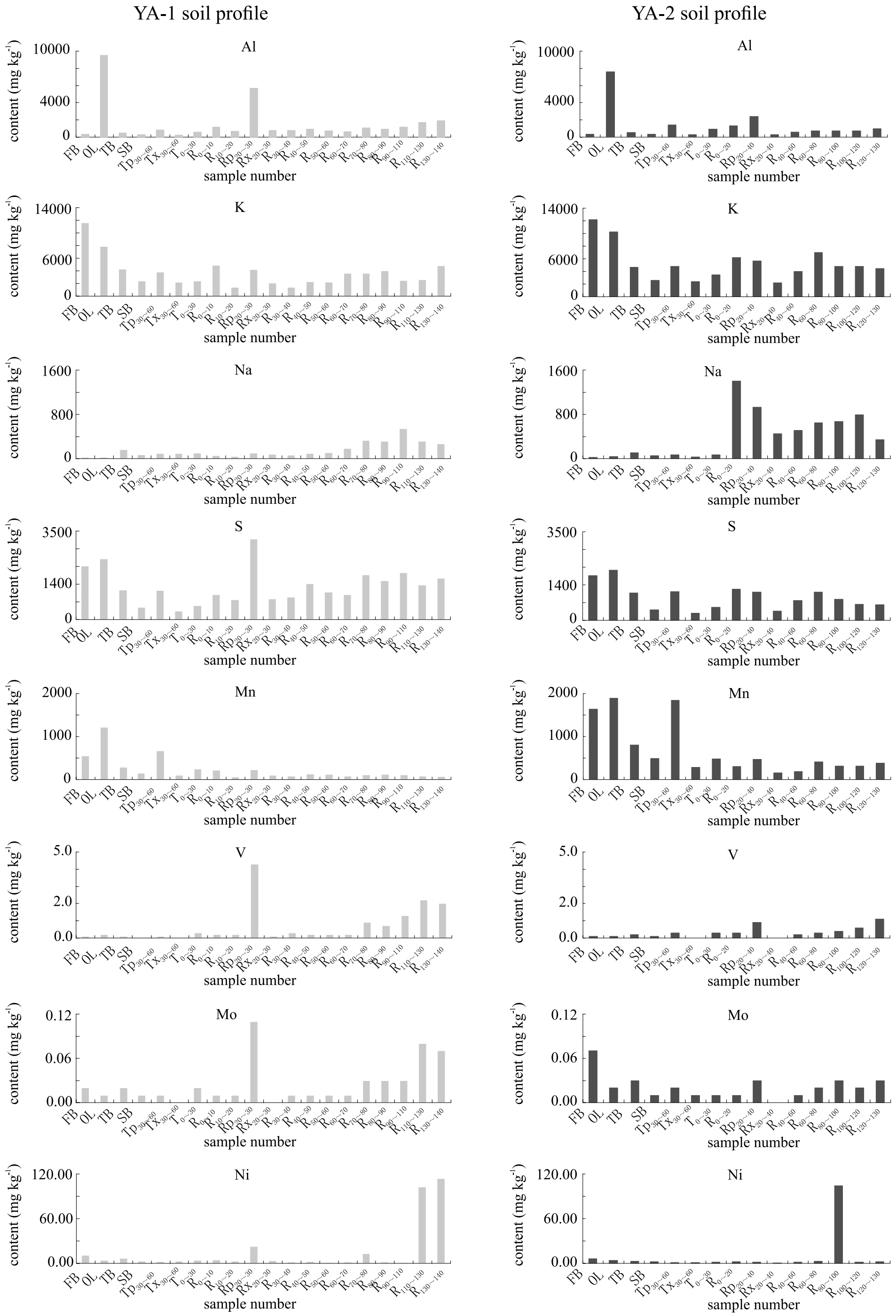
All mineral element concentrations in the trunk and root phloem are much higher than those in the xylem of the tea plants grown on the Yangai tea farm (Figure 3). It was similar to that in the phloem of tobacco stem (Hocking 1980, Marschner 2012). This finding might be related to the role and function of the phloem in the plant (Marschner, 2012). The root phloem and the trunk phloem of the tea plant have vital functions in the absorption of mineral nutrients from the soil and transport of mineral elements to the aerial parts, respectively. And the trunk and root xylem mainly play a supporting or fixing role.

All mineral element concentrations in the tertiary branch in the tea plant are much higher than those in the secondary branch (Figure 3). This finding is similar to Han et al. (2009) results: the order of Pb content in tea branches of 10-year-old Longjing 43 is production branch > lateral branch > trunk. Additionally, the mineral element content of the trunk phloem in the tea plant is much higher than in the trunk xylem (Figure 3). Thus, the mineral element content of the tertiary branch is higher than in their secondary branch, which might be caused by the branch being thinner, with a greater proportion of phloem per unit weight.

The mineral elements (e.g., Ca, K, P, S, Mg, Mn, and Zn) are relatively high in the tea plant. The Al content of the old leaves and the tea plant root phloem is higher than that in other organs of the tea plant (Figure 3). The content of Ca, P, Mn, and Zn in the aerial parts of the tea plant is significantly higher than in the underground parts. And the content of Fe, Na, Co, V, and Se in the aerial organs of the tea plant is significantly lower than in the underground part. The content of K, Mg, and S in all organs of the tea plant is relatively high but not regular, and the content of Mo, Ni, and Cu in the organs of the tea plant is lower and shows no marked regularity (Figure 3).

Source of mineral elements in soil profile

Except for the considerable enrichment with Se and the slight enrichment with Fe, S, Mo, V, and Zn, the concentrations of the other mineral elements in the soil in the Yangai tea farm are generally not enriched or only slightly enriched. The average element enrichment factors for the mineral elements Ca, Fe, K, Mg, Na, P, S, Mn, Mo, Se, V, Co, Cu, Ni, and Zn in the soil profile of the Yangai tea farm are respectively 0.007, 1.766, 0.476, 0.164, 0.019, 0.422, 1.546, 0.785, 1.906, 13.795, 1.049, 0.829, 0.942, 0.651 and 1.772 (Table 3). And they range from 0.003 to 0.014, 0.931 to 8.421, 0.397 to 0.529, 0.104 to 0.184, 0.016 to 0.024, 0.320 to 0.633, 0.224 to 2.831, 0.145 to 10.089, 1.567 to 2.426, 11.235 to 25.559, 0.949 to 1.125, 0.514 to 4.616, 0.730 to 1.252, 0.547 to 0.753, and 1.554 to 2.958, respectively. According to Sutherland (2000) and Chen et al. (2007), $EF < 1$, $1 \leq EF < 3$, $3 \leq EF < 5$, $5 \leq EF < 10$, $10 \leq EF < 25$, $25 \leq EF < 50$, and $EF \geq 50$ correspond to no enrichment, light enrichment, moderate enrichment, moderate-considerable enrichment, considerable enrichment, essential enrichment, and extreme enrichment, respectively. Except for the average enrichment factors for Fe, S, Mo, V, and Zn determined in the range of 1 to 3 and Se equal 13.795, the average enrichment factors of the other mineral elements in the soil of the Yangai tea farm are all lower than 1 (Figure 4). This reveals that the soil of the Yangai tea farm is generally not enriched in terms of the content of 16 mineral elements, except Fe, S, Mo, V, and Zn, which are slightly enriched, and Se, which is considerably enriched.


YA-1 soil profile
YA-2 soil profile
Al
K
Na
S
Mn
V
Mo
Ni
content (mg kg-1)
sample number
10000
4000
0
14000
6000
1600
800
3500
1400
2000
1000
5.0
2.0
0.0
0.12
0.06
0.00
120.00
60.00
FB
OL
TB
SB

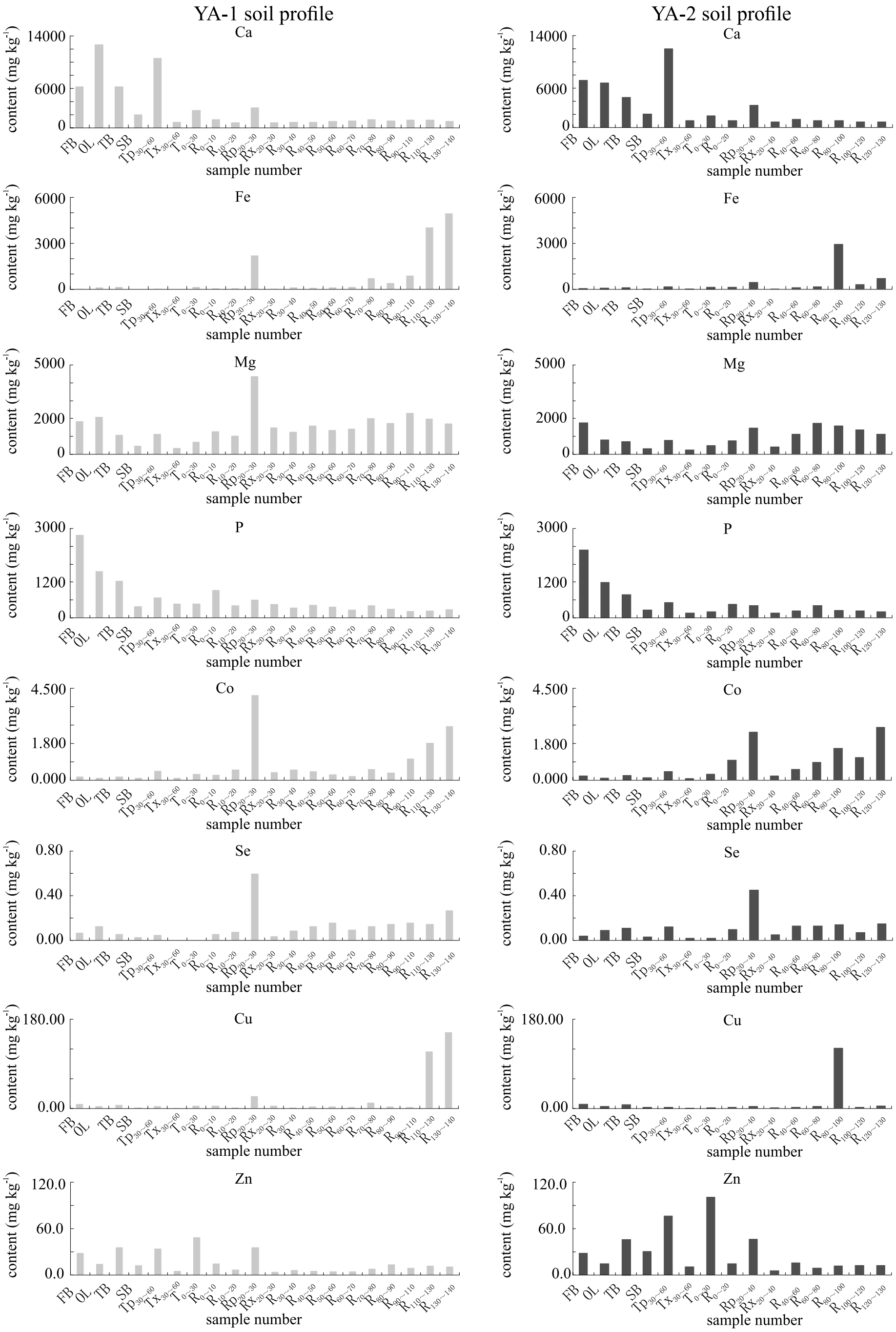


Fig. 3. Variation of mineral elements in various organs of the tea plant in the Yangai tea farm of Guiyang City

Table 3

Enrichment factor of mineral elements of the soil profile in the Yangai tea farm of Guiyang City

Sample profile	Sample depth (cm)	Al	Ca	Fe	K	Mg	Na	P	S	Mn	Mo	Se	V	Co	Cu	Ni	Zn
YA-1	0~10	1.000	0.006	1.020	0.513	0.176	0.024	0.460	1.890	0.471	1.965	16.378	1.055	0.560	0.886	0.619	1.614
	10~20	1.000	0.005	0.954	0.456	0.164	0.021	0.426	1.944	0.320	1.670	14.439	1.064	0.531	0.730	0.547	1.557
	20~30	1.000	0.005	0.931	0.454	0.165	0.022	0.401	2.231	0.317	1.740	14.502	1.080	0.534	0.749	0.573	1.554
	30~40	1.000	0.005	0.932	0.450	0.165	0.019	0.323	2.261	0.187	1.794	13.063	1.074	0.525	0.789	0.611	1.577
	40~50	1.000	0.005	1.375	0.450	0.160	0.017	0.379	2.512	0.145	2.147	13.063	1.084	0.515	0.894	0.631	1.652
	50~60	1.000	0.007	1.887	0.449	0.161	0.018	0.437	2.671	0.164	2.426	13.890	1.044	0.553	0.982	0.707	1.697
	60~70	1.000	0.011	2.116	0.454	0.165	0.017	0.468	2.553	0.200	2.027	13.274	1.018	0.621	1.000	0.655	1.858
	70~80	1.000	0.010	1.312	0.479	0.166	0.018	0.402	2.087	0.157	1.664	12.059	1.050	0.625	0.950	0.711	1.843
	80~90	1.000	0.008	1.431	0.462	0.167	0.017	0.550	1.539	0.158	1.829	11.431	0.978	0.629	0.954	0.753	1.878
	90~110	1.000	0.006	1.915	0.479	0.163	0.018	0.632	0.472	0.184	2.109	12.284	1.015	0.624	1.004	0.730	1.948
	110~130	1.000	0.006	1.347	0.465	0.171	0.017	0.413	0.451	0.209	1.644	11.715	1.041	0.729	0.910	0.698	1.799
	130~140	1.000	0.004	2.938	0.526	0.153	0.020	0.437	0.609	0.193	2.295	**15.827**	1.125	0.652	1.124	0.690	1.696

cont. Table 3

Sample profile	Sample depth (cm)	Al	Ca	Fe	K	Mg	Na	P	S	Mn	Mo	Se	V	Co	Cu	Ni	Zn
YA-2	0~20	1.000	0.005	1.126	0.492	0.170	0.022	0.378	2.544	0.285	1.852	14.696	1.072	0.514	0.824	0.582	1.617
	20~40	1.000	0.006	1.313	0.496	0.172	0.020	0.350	2.831	0.273	1.865	13.382	1.061	0.586	0.894	0.575	1.644
	40~60	1.000	0.014	1.187	0.529	0.184	0.020	0.320	1.773	0.200	1.905	13.168	1.092	0.648	0.994	0.681	1.731
	60~80	1.000	0.010	1.295	0.511	0.177	0.018	0.353	1.168	0.231	1.806	12.148	1.057	0.556	1.002	0.683	1.770
	80~100	1.000	0.006	1.121	0.506	0.175	0.017	0.338	0.224	0.203	1.842	11.633	1.047	0.533	1.006	0.681	1.745
	100~120	1.000	0.005	1.157	0.481	0.162	0.017	0.353	0.432	0.245	1.798	11.235	1.015	0.571	0.958	0.699	1.725
	120~122	1.000	0.006	1.537	0.462	0.159	0.018	0.388	0.234	1.464	1.567	12.148	0.949	1.460	0.935	0.617	1.579
	122~130	1.000	0.003	8.421	0.397	0.104	0.016	0.633	0.492	10.089	2.181	**25.559**	1.060	4.616	1.252	0.578	2.958
Minimum		1.000	0.003	0.931	0.397	0.104	0.016	0.320	0.224	0.145	1.567	11.235	0.949	0.514	0.730	0.547	1.554
Maximum		1.000	0.014	8.421	0.529	0.184	0.024	0.633	2.831	10.089	2.426	25.559	1.125	4.616	1.252	0.753	2.958
Average		1.000	0.007	1.766	0.476	0.164	0.019	0.422	1.546	0.785	1.906	13.795	1.049	0.829	0.942	0.651	1.772

Note: bold figures mean that the actual value should be less than this value.

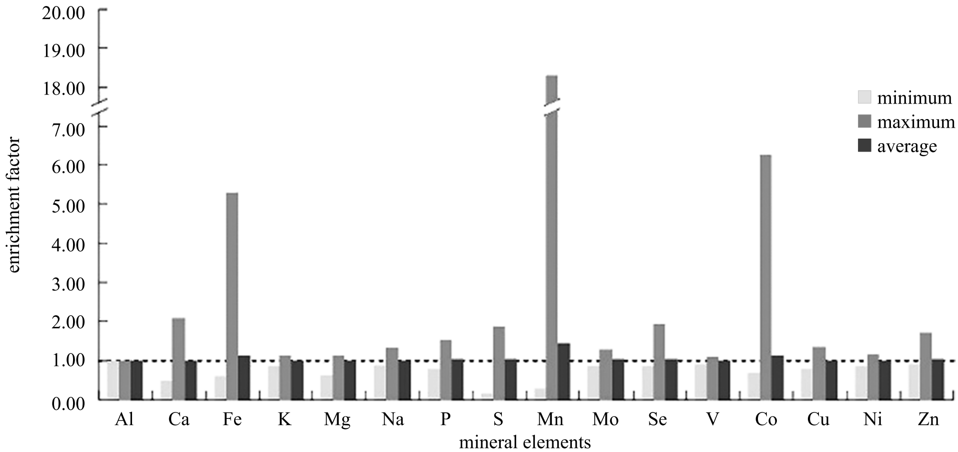


Fig. 4. Enrichment factors of mineral elements in the soil of the Yangai tea farm in Guiyang City

The Fe, S, Mo, V, and Zn, the Se, and other mineral elements are mainly from natural sources and human sources, human activities, and natural sources in the soil of the Yangai tea farm, respectively. The enrichment factor of a mineral element could help trace the soil mineral element's source (Hu et al. 2013, Peng et al. 2017*a*). The soil mineral elements are primarily derived from the naturally weathered bedrock (Peng et al. 2017*a*, Yang et al. 2010, 2011) or particular physical geographical background (Yu et al. 2014) or human activities (Peng et al. 2017*a*, Yu et al. 2014). Moreover, an EF of less than one, between 1 and 3, and greater than three indicates that the element originated predominantly from natural sources, both natural sources and anthropogenic activities, and from anthropogenic activities, respectively (Hu et al. 2013, Peng et al. 2021). As described in Figure 4, the average enrichment factors of Se are over 3, the average enrichment factors of Fe, S, Mo, V, and Zn range from 1 to 3, the average enrichment factors of other mineral elements in the soil of the Yangai tea farm are all lower than 1. Except the enrichment factors of Fe, Mn, and Co in the hard iron layer at the bottom of the YA-2 soil profile, which are more than 3, the enrichment factors of the other mineral elements in the soil of the Yangai tea farm are all less than 3 (Table 3). These show that the Fe, S, Mo, V, and Zn mineral elements in the soil of the Yangai tea farm are both from natural and human sources. The Se might be chiefly affected by human activities. And the other mineral elements are mainly from natural sources.

Absorption and transport of mineral elements by tea plants

The tea plant has a good ability to absorb Ca, S, and P. The average bioconcentration factors of mineral elements in the tea plant in the Yangai tea farm are in the following order: Ca > S > P > Mn > Na > K > Mg > Cu > > Ni > Se, Zn > Co > Al > Fe > Mo > V (Table 4). The bioconcentration factors of mineral elements Al, Ca, Fe, K, Mg, Na, P, S, Mn, Mo, Se, V, Co, Cu, Ni, and Zn are from 0.002 to 0.077, 1.882 to 29.882, 0.000 to 0.037, 0.094 to 0.817, 0.043 to 0.760, 0.030 to 2.121, 0.244 to 4.260, 0.487 to 5.345, 0.076 to 2.410, 0.002 to 0.026, 0.002 to 0.026, 0.020 to 0.600, 0.000 to 0.020, 0.003 to 0.151, 0.013 to 0.151, 0.013 to 1.997, 0.008 to 1.547 and 0.025 to 0.551, respectively. Their average values are 0.012, 6.958, 0.004, 0.294, 0.230, 0.396, 0.911, 1.941, 0.535, 0.006, 0.119, 0.003, 0.028, 0.208, 0.171 and 0.119, respectively. These show that the tea plant has a good ability to absorb Ca, S, and P in the Yangai tea farm.

The trunk and root phloem, flower buds, old leaves, roots, and stems of the tea plant grown on the Yangai tea farm had a relatively strong ability to absorb mineral elements such as K, Ca, Mg, S, P, and Mn. The content of Ca, P, Mn, and Zn in the tea plant aerial parts is significantly higher than in the underground part (Figure 3). The average bioconcentration factors of Ca and S in the tea plant from the Yangai tea farm are higher than 1, especially in the case of Ca (Figure 5). These show that the tea plant has a relatively strong ability to absorb and enrich Ca and S, especially the Ca element. And the tea plant has a weak ability to absorb and accumulate other mineral elements. The bioconcentration factors of Ca, S, P, and Mn in the old leaves of the tea plant grown on the Yangai tea farm are all greater than 1 (Table 4), indicating that the old leaves of the tea plant have a relatively strong ability to accumulate Ca, S, P, and Mn. Similar result were obtained in Leishan County (Peng et al. 2017*b*). The cloned tea plants in the Wushwush tea plantation in Ethiopia have a high enrichment capacity for K and Mn (Yemane et al. 2008). The tea in Guangxi has a relatively strong ability to accumulate Ca and Mn (Zhou, Li 2008). In addition, the bioconcentration factors of K, Ca, Mg, S, P, and Mn in flower buds, old leaves, and the trunk and root phloem of tea plants from the Yangai tea farm are higher than those of these mineral elements in other organs (Table 4). It shows that flower

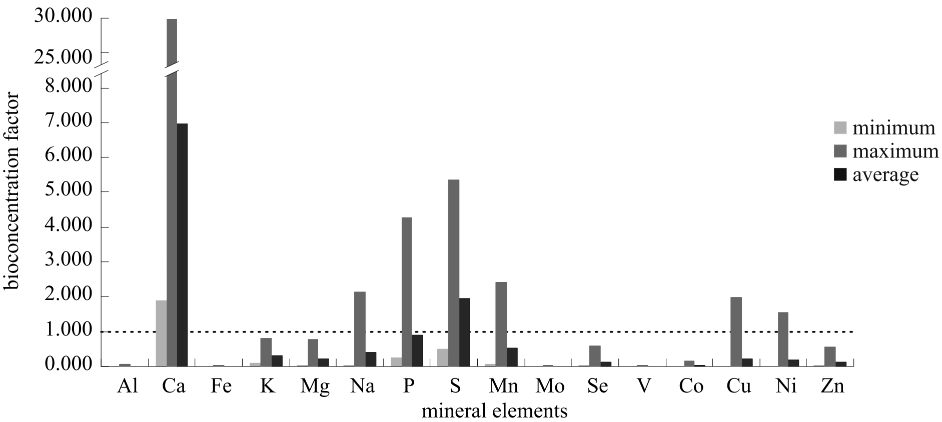


Fig. 5. Bioconcentration factors of mineral elements in the tea plant in the Yangai tea farm of Guiyang City

Table 4

Bioconcentration factors of mineral elements in different organs of the tea plant in the Yangai tea farm of Guiyang City

Sample type	Sample location	Al	Ca	Fe	K	Mg	Na	P	S	Mn	Mo	Se	V	Co	Cu	Ni	Zn
Flower bud	flower bud of YA-1	0.003	14.824	0.000	0.777	0.324	0.030	4.260	3.563	0.703	0.005	0.070	**0.000**	0.007	0.121	0.147	0.159
Older leaf	older leaf of YA-1	0.077	29.882	0.001	0.529	0.367	0.030	2.412	4.034	1.556	0.002	0.130	0.001	0.004	0.063	0.050	0.082
Tertiary branch	main branch of secondary branch of YA-1	0.004	14.824	0.001	0.288	0.190	0.242	1.908	1.966	0.369	0.005	0.060	0.000	0.007	0.107	0.092	0.198
Secondary branch	main branch of trunk of YA-1	0.002	4.706	0.000	0.161	0.085	0.106	0.611	0.807	0.191	0.002	0.030	**0.000**	0.005	0.036	0.042	0.073
Trunk phloem	trunk aboveground from 30 to 60 cm of YA-1	0.007	24.941	0.000	0.254	0.197	0.136	1.053	1.933	0.851	0.002	0.050	0.000	0.017	0.074	0.028	0.189
Trunk xylem	trunk aboveground from 30 to 60 cm of YA-1	0.002	2.118	0.000	0.147	0.062	0.136	0.748	0.555	0.119	**0.002**	**0.020**	**0.000**	0.004	0.025	0.037	0.031
Trunk	trunk aboveground from 0 to 30 cm of YA-1	0.005	6.353	0.001	0.161	0.123	0.152	0.748	0.924	0.312	0.005	**0.020**	0.001	0.012	0.075	0.052	0.268
Root	root underground from 0 to 10 cm of YA-1	0.010	3.059	0.001	0.328	0.225	0.076	1.435	1.647	0.274	0.002	0.060	0.001	0.010	0.083	0.058	0.083
Root	root underground from 10 to 20 cm of YA-1	0.006	1.882	0.001	0.094	0.184	0.061	0.641	1.328	0.076	0.002	0.080	0.001	0.019	0.033	0.040	0.039
Root phloem	root underground from 20 to 30 cm of YA-1	0.046	7.294	0.017	0.281	0.760	0.152	0.947	5.345	0.283	0.026	0.600	0.020	0.151	0.332	0.304	0.199
Root xylem	root underground from 20 to 30 cm of YA-1	0.006	1.882	0.000	0.141	0.261	0.121	0.718	1.378	0.129	**0.002**	0.040	0.000	0.014	0.081	0.042	0.025
Root	root underground from 30 to 40 cm of YA-1	0.006	2.118	0.001	0.094	0.220	0.091	0.550	1.496	0.096	0.002	0.090	0.001	0.020	0.038	0.022	0.037
Root	root underground from 40 to 50 cm of YA-1	0.008	2.118	0.001	0.154	0.281	0.136	0.672	2.370	0.159	0.002	0.130	0.001	0.016	0.058	0.032	0.030
Root	root underground from 50 to 60 cm of YA-1	0.006	2.353	0.001	0.147	0.239	0.167	0.580	1.832	0.154	0.002	0.160	0.001	0.011	0.055	0.019	0.027

cont. Table 4

Sample type	Sample location	Al	Ca	Fe	K	Mg	Na	P	S	Mn	Mo	Se	V	Co	Cu	Ni	Zn
Root	root underground from 60 to 70 cm of YA-1	0.005	2.588	0.001	0.241	0.251	0.273	0.427	1.664	0.105	0.002	0.100	0.001	0.008	0.043	0.021	0.027
Root	root underground from 70 to 80 cm of YA-1	0.009	3.059	0.006	0.241	0.352	0.500	0.656	2.975	0.143	0.007	0.130	0.004	0.020	0.161	0.175	0.045
Root	root underground from 80 to 90 cm of YA-1	0.007	2.588	0.003	0.268	0.306	0.470	0.473	2.571	0.150	0.007	0.150	0.003	0.014	0.053	0.020	0.076
Root	root underground from 90 to 110 cm of YA-1	0.010	2.824	0.007	0.167	0.402	0.818	0.366	3.109	0.140	0.007	0.160	0.006	0.039	0.050	0.019	0.054
Root	root underground from 110 to 130 cm of YA-1	0.014	2.824	0.030	0.174	0.348	0.470	0.382	2.303	0.103	0.019	0.150	0.010	0.066	1.504	1.391	0.069
Root	root underground from 130 to 140 cm of YA-1	0.015	2.353	0.037	0.321	0.300	0.409	0.458	2.739	0.085	0.016	0.270	0.009	0.096	1.997	1.547	0.061
Flower bud	flower bud of YA-2	0.003	16.941	0.000	0.817	0.306	0.030	3.481	2.958	2.091	0.016	0.040	0.000	0.008	0.111	0.084	0.154
Older leaf	older leaf of YA-2	0.062	16.000	0.001	0.690	0.142	0.061	1.817	3.328	2.410	0.005	0.090	0.000	0.004	0.058	0.052	0.080
Tertiary branch	main branch of secondary branch of YA-2	0.005	10.824	0.001	0.315	0.121	0.167	1.191	1.832	1.020	0.007	0.110	**0.001**	0.008	0.108	0.035	0.252
Secondary branch	main branch of trunk of YA-2	0.003	4.941	0.000	0.174	0.057	0.076	0.397	0.706	0.630	0.002	0.030	0.000	0.005	0.036	0.028	0.165
Trunk phloem	trunk aboveground from 30 to 60 cm of YA-2	0.011	28.235	0.001	0.321	0.137	0.106	0.779	1.899	2.346	0.005	0.120	0.001	0.015	0.034	0.018	0.417
Trunk xylem	trunk aboveground from 30 to 60 cm of YA-2	0.002	2.588	0.000	0.161	0.043	0.045	0.244	0.487	0.367	0.002	0.020	0.000	0.003	0.013	0.015	0.059
Trunk	trunk aboveground from 0 to 30 cm of YA-2	0.007	4.235	0.001	0.234	0.087	0.106	0.321	0.874	0.619	0.002	0.020	**0.001**	0.011	0.027	0.021	0.551
Root	root underground from 0 to 20 cm of YA-2	0.011	2.588	0.001	0.415	0.132	2.121	0.702	2.084	0.383	0.002	0.100	0.001	0.036	0.033	0.028	0.080

cont. Table 4

Sample type	Sample location	Al	Ca	Fe	K	Mg	Na	P	S	Mn	Mo	Se	V	Co	Cu	Ni	Zn
Root phloem	root underground from 20 to 40 cm of YA-2	0.019	8.000	0.003	0.382	0.255	1.409	0.626	1.882	0.603	0.007	0.450	0.004	0.085	0.060	0.025	0.252
Root xylem	root underground from 20 to 40 cm of YA-2	0.002	2.118	0.000	0.147	0.071	0.682	0.244	0.622	0.197	0.002	0.050	0.000	0.008	0.023	0.008	0.032
Root	root underground from 40 to 60 cm of YA-2	0.005	3.059	0.001	0.268	0.194	0.773	0.366	1.328	0.240	**0.002**	0.130	**0.001**	0.019	0.035	0.022	0.085
Root	root underground from 60 to 80 cm of YA-2	0.006	2.588	0.001	0.469	0.303	0.985	0.626	1.882	0.528	0.005	0.130	0.001	0.032	0.055	0.037	0.050
Root	root underground from 80 to 100 cm of YA-2	0.006	2.588	0.022	0.321	0.277	1.015	0.382	1.412	0.394	0.007	0.140	0.002	0.057	1.582	1.411	0.065
Root	root underground from 100 to 120 cm of YA-2	0.006	2.118	0.002	0.321	0.239	1.197	0.366	1.059	0.400	0.005	0.070	0.003	0.040	0.035	0.021	0.069
Root	root underground from 120 to 130 cm of YA-2	0.008	2.118	0.005	0.301	0.194	0.515	0.305	1.042	0.485	0.007	0.150	0.005	0.094	0.067	0.032	0.069
Minimum		0.002	1.882	0.000	0.094	0.043	0.030	0.244	0.487	0.076	0.002	0.020	0.000	0.003	0.013	0.008	0.025
Maximum		0.077	29.882	0.037	0.817	0.760	2.121	4.260	5.345	2.410	0.026	0.600	0.020	0.151	1.997	1.547	0.551
Average		0.012	6.958	0.004	0.294	0.230	0.396	0.911	1.941	0.535	0.006	0.119	0.003	0.028	0.208	0.171	0.119

Note: bold figures mean that the actual value should be less than this value.

buds, old leaves, and the trunk and root phloem of the tea plant have a relatively strong ability to absorb and enrich mineral elements such as K, Ca, Mg, S, P, and Mn.

The content of high reabsorption proficiency mineral elements (i.e., K, Mg, P, S, Mo, Cu, Ni, and Zn) in organs with active growth and exuberant metabolism (i.e., leaf buds and flower buds) of the tea plant is generally higher than in vegetative storage organs (e.g., old leaf). The content of K, Mg, P, S, Mo, Cu, Ni, and Zn in young leaves and flower buds of the tea plant is higher than in their senescent organs (such as old leaves) in tea plants on the Yangai tea farm (Table 5). In the process of tea growth, the content of P, Zn, S, Cu, K, Mg, and Ni in tender leaves of the tea plant was relatively high (Peng et al. 2017*b*). Reuse of a mineral element is defined as a mineral element of an organ with active growth and vigorous metabolism of a plant that can be transported from a vegetative storage organ through its phloem. The tea plant needs huge macronutrient mineral elements (i.e., K, Mg, and P) to participate in its life activities and material synthesis. And these elements belong to high reabsorption proficiency mineral elements. When the amount of a high reabsorption proficiency mineral element is inadequate for the organs with active growth and exuberant metabolism, the tea plant will transfer this mineral element from its nutrient storage organs (i.e., mature leaf, old leaf, root, and so on) – Huang, Xiao (1992). As a result, the content of high reabsorption proficiency mineral elements in the organs with active growth and exuberant metabolism in the tea plant is generally higher than in its vegetative storage organs (e.g., old leaf).

The content of low reabsorption proficiency mineral elements (i.e., Al, Ca, Mn) in vegetative storage organs (e.g., old leaf) of the tea plant is higher than in organs with active growth and exuberant metabolism (i.e., leaf buds and flower buds). The content of Al, Ca, and Mn in the old leaves of the tea plant in the Yangai tea farm is higher than in the young leaves and flower buds (Table 5). The Mn content of old leaves was significantly higher than that of stems, roots, and tender leaves (Shan et al. 2017). Fung et al. (2003) also found that the content of Ca, Al, and F in old tea leaves was higher than in tender leaves. In the process of tea growth, the content of Ca, Al, Fe, Cr, As, Pb, Cd, Mn, and Ba in the old leaves of the tea plant was higher than in the tender leaves (Peng et al. 2017*b*). The slight difference in the distribution of mineral elements in tea plants is due to the functions of different organs that might correlate with the mineral element properties and physiological effects (Sha, Zheng 1996). There are some main reasons for the high content of Al, Ca, and Mn in the old leaf of the tea plant (Huang, Xiao 1992): Firstly, the tea plant is an Mn-accumulating and Al-tolerant plant, which could predominantly fix these elements on the epidermis and palisade tissue cell wall (such as Al) or epidermis cell wall (such as Mn) to avoid the toxic effects on its healthy growth. Additionally, a low reabsorption proficiency mineral element is usually accumulated in organs with vegetative

Table 5
Content of mineral element in the tea plant in the Yangai tea farm of Guiyang City (mg kg^{-1})

Mineral elements	Flower bud	Tender leaf	Old leaf	Stem	Trunk xylem	Trunk phloem	Root	Root xylem	Root phloem
Al	355	600	8550	595	265	1110	1242	535	4050
Ca	6750	3700	9750	4410	1000	11300	1257.14	850	3250
Fe	51	200	108	94	15	113	903	30	1342
K	11900	18700	9100	3310	2300	4300	3752	2150	4950
Mg	1820	2100	1470	637	305	965	1593	960	2930
Na	20	/	30	84	60	80	391	265	515
P	2535	5900	1385	524	325	600	372	315	515
S	1940	2900	2190	713	310	1140	1192	595	2150
Mn	1095.5	890.0	1555.0	535.1	190.6	1253.5	191.5	128.0	347.5
Mo	0.05	/	0.02	0.02	0.01	0.02	0.03	0.01	0.07
Se	0.06	/	0.11	0.06	0.02	0.09	0.16	0.05	0.53
V	0.1	/	0.2	0.2	0.1	0.2	0.8	0.1	2.6
Co	0.206	/	0.113	0.242	0.108	0.447	1.127	0.310	3.265
Cu	8.96	18.80	4.66	4.14	1.50	4.17	23.42	4.02	15.11
Ni	8.51	/	3.77	2.71	1.93	1.71	18.50	1.85	12.11
Zn	28.7	53.0	14.9	40.4	8.3	55.5	12.9	5.2	41.3

Note: The data of tender leaves are cited from the literature (Chen et al. 2021), and '/' represents that no data were available. The other data are the average content of mineral elements in the corresponding organs of the tea plant in the sampling sites of YA-1 and YA-2 in this study.

storage and senescence (i.e., old leaf) of the tea plant, for example excessive Ca binds with the tea plant's organic acid to form calcium oxalate crystals. Thus, a low reabsorption proficiency mineral element could not or would rarely be mobilized for reuse so that the element's content of a vegetative storage organ (i.e., old leaf) is higher than in an organ with active growth and vigorous metabolism.

Effect of soil on mineral elements in tea plant

The soil of the Yangai tea farm, which is the primary source of mineral elements in various organs of the tea plant, could provide abundant mineral elements such as Mo, Se, V, Co, Cu, Ni, and Zn for the tea plant growth. Compared with the content of mineral elements in the continental crust, the content of Ca, Mg, and Na in the soil of the Yangai tea farm is significantly lower than in the continental crust (Figure 6). The content of mineral elements (i.e., Mo, Se, V, Co, Cu, Ni, and Zn) in the soil is markedly higher than in the crust. And the content of the other mineral elements is similar in the analyzed soil and in the crust. These findings show that the soil in the

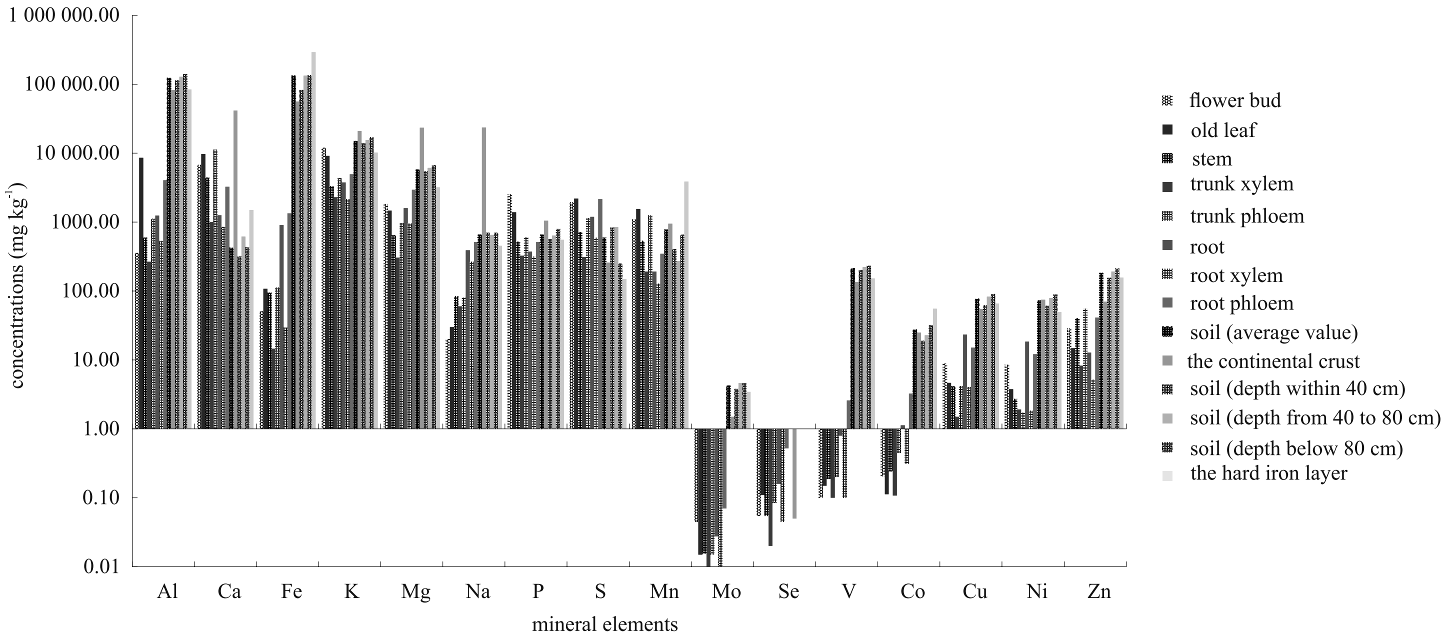


Fig. 6. Distribution of mineral elements in the system between tea plant and soil in the Yangai tea farm of Guiyang City

study area could provide abundance of mineral elements such as Mo, Se, V, Co, Cu, Ni, and Zn for the growth of the tea plant.

Except for the high content of Fe, Mn, and Co in the hard iron layer, the distribution of other mineral elements in the soil (the soil depth is within 40 cm, between 40 cm and 80 cm, and below 80 cm, respectively) does not change much in the Yangai tea farm (Figure 6). And except for the enrichment factors of Fe, Mn, and Co in the hard iron layer at the bottom of the soil profile, which are more than three, and the EF of Se, which is higher than 10, the enrichment factors of the other mineral elements in the soil of the Yangai tea farm are close to 1 (Table 3). These findings show that, except for Se, the distribution of mineral elements in the upper layer soil inherits that in the autochthonous soil and is not affected by human activities.

The distribution of most mineral elements in various organs (buds, old leaves, stems, and roots) of the tea plant in the Yangai tea farm is similar to that in the corresponding soil. It is similar to the distribution of mineral elements in old tea plants and in soil in Leishan County (Peng et al. 2017*b*). At the same time, the soil properties and changes can affect food and environmental quality (Gu et al. 2021). Sha and Zheng (1996) found that the mineral element content of the soil is a significant factor affecting the accumulation of mineral elements in tea plants. This finding shows that the mineral element distribution of the tea plant organs mainly originates from the soil and inherits the distribution of these elements in the autochthonous soil.

Although this study failed to distinguish whether the content of mineral elements in the tea plant mainly come from shallow or deep soil, it was determined that the root distribution depth of the tea plant in the Yangai tea farm reached at least 130 cm down the soil profile. If there were no physical restrictions (such as a high water level), the roots of tea plants could extend to a considerable depth (5-6 meters) and extract water from it (Carr 2017). About 2/3 of the nutrients of deep-rooted plants and trees are present at 2 m of the soil surface (Yost, Hartemink 2020). The storage and availability of nutrients, essential for agricultural production and plant growth, are affected by soil depth (Yost, Hartemink 2019). Deforestation, which affects depth distributions of carbon inputs from roots, may also affect net carbon storage in the soil (Nepstad et al. 1994). The deep roots of perennial forage plants (especially *Panicum maximum* and *Festuca arundinaceae*) could absorb water to improve crop production in water-scarce environments (Sekiya et al. 2011). McMahon et al. (2019) found that fertilizer application, redistribution of nutrients from biomass, and possible inputs from the atmosphere or deep soil maintained soil nutrient stocks in eucalyptus plantations over multiple harvests. The deep roots provide individual plants with vital functions (i.e., nutrient and water uptake), and influence soil pedogenesis and carbon storage (Maeght et al. 2013). The content of Co, Fe, and Mn in the soil of the Yangai tea farm shows a gradual increase with increasing soil depth of under 80 cm (Figure 2). It was determined that the tea plants in the Yangai tea farm absorbed mineral elements (i.e., Co, Fe, and Mn) from the soil to a depth of 130 cm. Thus, the deep soil layer will also affect the absorption of mineral elements by the tea plants to a certain extent. Therefore, the mineral element supply from the deep layer of the soil should also be considered when tea plant nutrition and fertilizer management plan is implemented in tea plant production (especially in tea plantations which are a few decades old).

CONCLUSIONS

The tea plant has a relatively good ability to absorb Ca and S, especially the Ca element, and flower buds, old leaves, and the trunk and root phloem of the tea plant have a high ability to absorb mineral elements (i.e., K, Ca, Mg, S, P, and Mn). Additionally, the content of low reabsorption proficiency mineral elements (i.e., Al, Ca, Mn) in vegetative storage organs (e.g., old leaf) of the tea plant is higher than in organs with active growth and exuberant metabolism (i.e., leaf buds and flower buds). And the content of high reabsorption proficiency mineral elements (i.e., K, Mg, P, S, Mo, Cu, Ni, and Zn) in the tea plant organs with active growth and exuberant metabolism is generally higher than in vegetative storage organs.

The soil of the Yangai tea farm is mainly an acidic and mineral soil. It can provide a wealth of mineral elements (e.g., Mo, Se, V, Co, Cu, Ni, and Zn) for the tea plant to grow. Thus, it is suitable for tea plantations. The mineral elements of each organ in the tea plant mainly come from the soil and inherit the distribution of these elements in the autochthonous soil. And the absorption range of mineral elements in tea plants at least reaches the soil layer within the depth of 130 cm in the research area. Therefore, the mineral element supply from the deep soil layer should also be considered when tea plant nutrition, nutrient absorption and fertilizer management are put into production (especially in tea gardens maintained for decades).

Conflict of interest

The authors declare no conflict of interest.

Author contribution

Yishu Peng collected the samples, conducted the experiments, and wrote the manuscript. Tao Jin conducted the experiments, Ruidong Yang designed the experiments and collected the samples, Rong Chen collected the samples, Jianxu Wang checked and reviewed the manuscript. And all authors critically revised the manuscript and approved the final version.

REFERENCES

Bai Y. 2019. *Tracing back to the origin of theoretical problems in plant nutrition*. J. Plant Nutr. Fert., 25, 1-10. (in Chinese). https://doi.org/10.11674/zwyf.19011

Bhat R., Kiran K., Arun A.B., Karim A.A. 2010. *Determination of mineral composition and heavy metal content of some nutraceutically valued plant products*. Food Anal. Method., 3: 181-187. DOI: 10.1007/s12161-009-9107-y

Carr M.K.V. 2017. *Advances in Tea Agronomy*. New York, NY, Cambridge University Press. DOI: 10.1017/9781316155714

Chen C.W., Kao C.M., Chen C.F., Dong C.D. 2007. *Distribution and accumulation of heavy metals in the sediments of Kaohsiung Harbor, Taiwan*. Chemosphere, 66: 1431-1440. https:// //doi.org/10.1016/j.chemosphere.2006.09.030

Chen R., Yang R., Peng Y., Ren H., Long J., Han X., Lang X. 2021. *Agricultural geological environment of the featured crops in Guizhou*. Sci Press, Beijing City. (in Chinese)

Ding Z., Jia S., Wang Y., Xiao J., Zhang Y. 2017. *Phosphate stresses affect ionome and metabolome in tea plants*. Plant Physiol. Bioch., 120: 30-39. https://doi.org/10.1016/j.plaphy.2017.09.007

Fung K., Zhang Z., Wong J., Wong M. 2003. *Aluminium and fluoride concentrations of three tea varieties growing at Lantau Island, Hong Kong*. Environ. Geochem. Hlth., 25: 219-232. https://doi.org/10.1023/A:1023233226620

Gong J. 2010. *Guiyang tea industry and tea comprehensive practical technology*. Guizhou Science and Technology Publishing House Co., Ltd., Guiyang City. (in Chinese)

Gu B., Chen D., Yang Y., Vitousek P., Zhu Y.-G. 2021. *Soil-Food-Environment-Health Nexus for Sustainable Development*. Research, 2021, 9804807. DOI: 10.34133/2021/9804807

Guardia M.D.L. Garrigues S. 2015. *Handbook of Mineral Elements in Food*. John Wiley & Sons, Ltd.

Han W., Yang Y., Liang Y., Shi Y., Ma L., Ruan L., Tang J. 2009. *Pb absorpting and accumulation in tea plants*. J. Tea Sci., 29: 200-206. (in Chinese)

Hocking P.J. 1980. *The Composition of Phloem Exudate and Xylem Sap from Tree Tobacco (Nicotiana glauca* Grah.*)*. Ann. Bot-London., 45: 633-643. DOI: 10.1093/oxfordjournals.aob.a085871

Hu Y., Liu X., Bai J., Shih K., Zeng E.Y., Cheng H. 2013. *Assessing heavy metal pollution in the surface soils of a region that had undergone three decades of intense industrialization and urbanization*. Environ. Sci. Pollut. R., 20: 6150-6159. https://doi.org/10.1007/s11356-013--1668-z

Huang P.M. 2004. *Soil mineral – organic matter-microorganism interactions: Fundamentals and impacts*. Adv Agron. Academic Press. https://doi.org/10.1016/S0065-2113(03)82006-0

Huang Y. Xiao L. 1992. *Nutritional physiology and soil management in tea plant*. Hunan Sci. Technol. Publishing House, Changsha City. (in Chinese)

Maeght J.-L., Rewald B., Pierret A. 2013. *How to study deep roots - and why it matters*. Fron. Plant Sci., 4: 299. DOI: 10.3389/fpls.2013.00299

Marschner P. 2012. *Marschner's Mineral Nutrition of Higher Plants*. Third Edition. Elsevier Ltd.

McMahon D.E., Vergütz L., Valadares S.V., Silva I.R. d., Jackson R.B. 2019. *Soil nutrient stocks are maintained over multiple rotations in Brazilian Eucalyptus plantations*. For Ecol. Manag., 448: 364-375. https://doi.org/10.1016/j.foreco.2019.06.027

Mo Q., Wang W., Lambers H., Chen Y., Yu S., Wu C., Fan Y., Zhou Q., Li Z., Wang F. 2021. *Response of foliar mineral nutrients to long-term nitrogen and phosphorus addition in a tropical forest*. Funct. Ecol., 35: 2329-2341. https://doi.org/10.1111/1365-2435.13896

Nepstad D.C., de Carvalho C.R., Davidson E.A., Jipp P.H., Lefebvre P.A., Negreiros G.H., da Silva E.D., Stone T.A., Trumbore S.E., Vieira S. 1994. *The role of deep roots in the* *hydrological and carbon cycles of Amazonian forests and pastures*. Nature, 372: 666-669. DOI: 10.1038/372666a0

Peng Y., Chen J., Wei H., Li S., Jin T., Yang R. 2018*a*. *Distribution and transfer of potentially toxic metal(loid)s in Juncus effusus from the indigenous zinc smelting area, Northwest Region of Guizhou Province, China*. Ecotox. Environ. Safe., 152: 24-32. https://doi.org/ /10.1016/j.ecoenv.2018.01.026

Peng Y., Chen R., Yang R. 2017*a*. *Analysis of heavy metals in Pseudostellaria heterophylla in Baiyi Country of Wudang District*. J. Geochem. Explor., 176: 57-63. http://dx.doi.org/ /10.1016/j.gexplo.2016.02.011

Peng Y., Chen R., Yang R., Zhang J., Wen X. 2017*b*. *Analysis on Mineral Elements of Camellia sinensis Plantations in the Qingshuijiang of Leishan County*. J. Sichuan Agric. Univ., 35: 359-369. (in Chinese). DOI: 10.16036/j. issn.1000-2650.2017.03.012

Peng Y., Yang R., Jin T., Chen J., Zhang J. 2018*b*. *Risk assessment for potentially toxic metal(loid)s in potatoes in the indigenous zinc smelting area of northwestern Guizhou Province, China*. Food Chem. Toxicol., 120: 328-339. https://doi.org/10.1016/j.fct.2018.07.026

Peng Y., Yang R., Jin T., Chen J., Zhang J. 2021. *Potentially toxic metal(loid) distribution and migration in the bottom weathering profile of indigenous zinc smelting slag pile in clastic rock region*. PeerJ, 9, e10825. DOI: 10.7717/peerj.10825

Schunk P.F.T., Kalil I.C., Pimentel-Schmitt E.F., Lenz D., de Andrade T.U., Ribeiro J.S., Endringer D.C. 2016. *ICP-OES and micronucleus test to evaluate heavy metal contamination in commercially available Brazilian herbal teas*. Biol. Trace Elem. Res., 172: 258-265. DOI: 10.1007/s12011-015-0566-2

Sekiya N., Araki H., Yano K. 2011. *Applying hydraulic lift in an agroecosystem: forage plants with shoots removed supply water to neighboring vegetable crops*. Plant Soil, 341: 39-50. https://doi.org/10.1007/s11104-010-0581-1

Sha J. Zheng D. 1996. *Distributions of mineral elements in the organs of Huangdan, a cultivar for Oolong Tea*. J. Tea Sci., 16: 141-146. (in Chinese)

Shan R., Chen Y., Wang F. Lin D., Zang C. Gao J., Chen C., You Z., Yu W. 2017. *Concentrations and distributions of iron and manganese in parts of tea plant*. Fujian J. Agric. Sci., 32: 1207-1212. (in Chinese)

Smith B.J., Lucas E.A. 2020. *Influence of dietary factors and nutritional status on toxicity response to environmental pollutants*. In: *An Introduction to Interdisciplinary Toxicology*. Chapter 22. Pope, C. N. Liu, J. (Eds.), Academic Press. https://doi.org/10.1016/B978-0-12- -813602-7.00022-3

Song M., Liu Y. 1990. *Effect of biogeochemical cycle in tea garden on the soil acidification*. J. Tea Sci., 10: 19-26. DOI: 10.13305/ j. cnki.jts.1990.02.003

Sutherland R. 2000. *Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii*. Environm. Geol., 39: 611-627. https://doi.org/10.1007/s002540050473

Taylor S.R. 1964. *Abundance of chemical elements in the continental crust: a new table*. Geochim. Cosmochim. Acta, 28: 1273-1285. https://doi.org/10.1016/0016-7037(64)90129-2

Tolrà R., Martos S., Hajiboland R., Poschenrieder C. 2020. *Aluminium alters mineral composition and polyphenol metabolism in leaves of tea plants (Camellia sinensis)*. J. Inorg. Biochem., 204: 110956. https://doi.org/10.1016/j.jinorgbio.2019.110956

Weil R.R., Brady N.C. 2016. *The Nature and Properties of Soils*. 15th edition. Pearson Education Limited, England.

Xu, J. 2019. *Soil Science*. Fourth Edition. China Agriculture Press, Beijing City. (in Chinese)

Yang R., Ren H., Long J., Lang X. 2011. *Trace element and rare earth element content in main rock-type weathering soil in Guizhou Province and eco-environment effect*. J. Guizhou Univ. (Nat. Sci.), 28: 110-119. (in Chinese) DOI: 10.15958/j.cnki.gdxbzrb.2011.06.019

Yang T.-Y., Qi Y.-P., Huang H.-Y., Wu F.-L., Huang W.-T., Deng C.-L., Yang L.-T., Chen L.-S.

2020. *Interactive effects of pH and aluminum on the secretion of organic acid anions by roots and related metabolic factors in Citrus sinensis roots and leaves*. Environ. Pollut., 262: 114303. DOI: 10.1016/j.envpol.2020.114303

Yang T., Zhu Z., Gao Q., Rao Z., Han J., Wu Y. 2010. *Trace element geochemistry in topsoil from East China*. Environ. Earth Sci., 60: 623-631. https://doi.org/10.1007/s12665-009--0202-6

Yemane M., Chandravanshi B.S., Wondimu T. 2008. *Levels of essential and non-essential metals in leaves of the tea plant (Camellia sinensis* L.*) and soil of Wushwush farms, Ethiopia*. Food Chem., 107: 1236-1243. http://dx.doi.org/10.1016/j.foodchem.2007.09.058

Yost J.L., Hartemink A.E. 2019. *Effects of carbon on moisture storage in soils of the Wisconsin Central Sands, USA*. Eur. J. Soil Sci., 70: 565-577. DOI: 10.1111/ejss.12776

Yost J.L., Hartemink A.E. 2020. *How deep is the soil studied – an analysis of four soil science journals*. Plant Soil, 10.1007/s11104-020-04550-z

Yu H., Ni S., He Z., Zhang C., Nan X., Kong B., Weng Z. 2014. *Analysis of the spatial relationship between heavy metals in soil and human activities based on landscape geochemical interpretation*. J. Geochem. Explor., 146: 136-148. https://doi.org/10.1016/j.gexplo.2014.08.010

Zhang H., Chen J., Zhu L., Yang G., Li D. 2014. *Anthropogenic mercury enrichment factors and contributions in soils of Guangdong Province, South China*. J. Geochem. Explor., 144: 312-319. https://doi.org/10.1016/j.gexplo.2014.01.031

Zhang J., Yang R., Chen R., Peng Y., Wen X., Gao L. 2018. *Accumulation of heavy metals in tea leaves and potential health risk assessment: A case study from Puan County, Guizhou Province, China*. Int. J. Environm. Res. Pub. He., 15: 133. DOI: 10.3390/ijerph15010133

Zhou Y., Li M. 2008. *Heavy metal contamination and transportation in soil-tea leaf-tea liquor system in two tea gardens of Guangxi*. J. Agro-Environ. Sci., 27: 2151-2157. (in Chinese) DOI: 10.19303/j.issn.1008-0384.2017.011.008