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Research Article

Features of seasonal biogeochemical element migration in the "soil-plant" system: A case study of Bambusoideae in the Bidoup-Nui Ba National Park (Central Vietnam)

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Abstract

The article presents unique research conducted in Bidoup-Nui Ba National Park, Vietnam, focusing on the biogeochemical element migration in soil and plants. The study aimed to identify element content changes, biological accumulation, and biogeochemical mobility during wet and dry seasons across different landscape conditions. The research revealed the active elements involved in migration and accumulation, assessed mobility and accumulation in bamboo organs, and highlighted the peculiarities within the "soil-plant" system. The study found that the uptake of certain microelements by plants is influenced by landscape facies and moisture conditions. For example, Zn, Cu, and Co were introduced through plant litter during the wet season and accumulated, while Mo accumulation was more pronounced in the dry season. Furthermore, the research observed variations in biological uptake by bamboo organs, with different landscape conditions and seasons playing a role. The biogeochemical mobility of elements in bamboo organs increased significantly with soil moisture during the wet season. Overall, the research provided insights into element accumulation and biogeochemical migration. Notably, the accumulation of element B was found to increase with soil moisture, while its reduction was associated with slope process activation during the wet season.

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Introduction

Bamboo plants are an important component of many terrestrial ecosystems, particularly in tropical and subtropical regions. As members of the Bambusoideae subfamily, bamboos exhibit unique physiological and ecological characteristics that influence the cycling of nutrients and biogeochemical elements within the soil-plant system. Understanding the seasonal dynamics of these processes is crucial for characterizing the role of bamboo in ecosystem function and nutrient budgets (Li et al., 2016; Ranieri et al., 2021; Liang et al., 2022; Ranieri et al., 2022). The study of biogeochemical element migration between soils and plants remains an underexplored area of research in Vietnam. Previous works have primarily focused on assessing heavy metal pollution, particularly in agricultural soils and vegetable crops around urban areas. However, the comprehensive investigation of element cycling and availability within natural ecosystems, such as montane tropical forests, has been largely overlooked. Studies reveal that most concentrate on soil pollution, while fewer studies address plant-related aspects, typically focusing on the accumulation of heavy metals in crop plants. Notable examples include the research by Huong (2010), Tuyet (2016), Nguyen et al. (2017), and Thụy (2018), which investigated heavy metal contamination in soils, waters, and agricultural products. Several other studies, such as those by Phuong et al. (2007), Huong et al. (2010), and Duc (2014), analyzed metal concentrations in various plant species. However, only a few studies, like those by Nguyen et al. (2017) and Tuyet (2016), considered the interrelationships within the 'soil-plant' system.

Research on phytoremediation, the use of plants to remove pollutants from the environment, has also been conducted in Vietnam (Duong and Tram, 2015; Nguyen, 2016; Nguyen, 2018a; Nguyen, 2018b). Yet, the broader aspects of biogeochemical element migration in natural ecosystems have largely been neglected. Among the studies reviewed, only a few were carried out in mountainous areas, including natural forests, and these primarily examined a limited number of elements in soils.

The present study aimed to investigate the characteristics and patterns of microelement content variations in the 'soil-plant' system, their biological accumulation, and biogeochemical mobility during the wet and dry seasons within the Bidoup-Nui Ba National Park, a montane tropical forest in Central Vietnam. The findings of this study will contribute to a deeper understanding of the role of bamboo in regulating nutrient cycling and ecosystem processes within the montane tropical forests of the Bidoup-Nui Ba National Park. The insights gained may also inform sustainable management practices for bamboo-dominated landscapes and help predict the potential impacts of environmental change on these valuable natural resources.

Materials and Methods

Study area

The research was conducted in Central Vietnam, specifically in Bidoup-Nui Ba National Park. Within the national park, a key study area was selected (Figure 1). The rationale for selecting this area as a landscape-ecological monitoring site has been described in previous studies by the authors (Gorbunov, 2018; Kotlov et al., 2018).

Soil profiles along the catenas were established in relation to elements of the structural-denudational relief - at the ridge top, the slope of the structural ridge, and the footslope (Figure 2). Soil samples were collected at the end of the dry season to determine the accumulation levels of elements in organogenic horizons during the decomposition of litter biomass. Additionally, samples were collected at the end of the wet season to identify the most labile elements involved in biogeochemical migration processes and to assess the influence of landscape conditions on the accumulation and migration of the studied elements. (Figure 2).

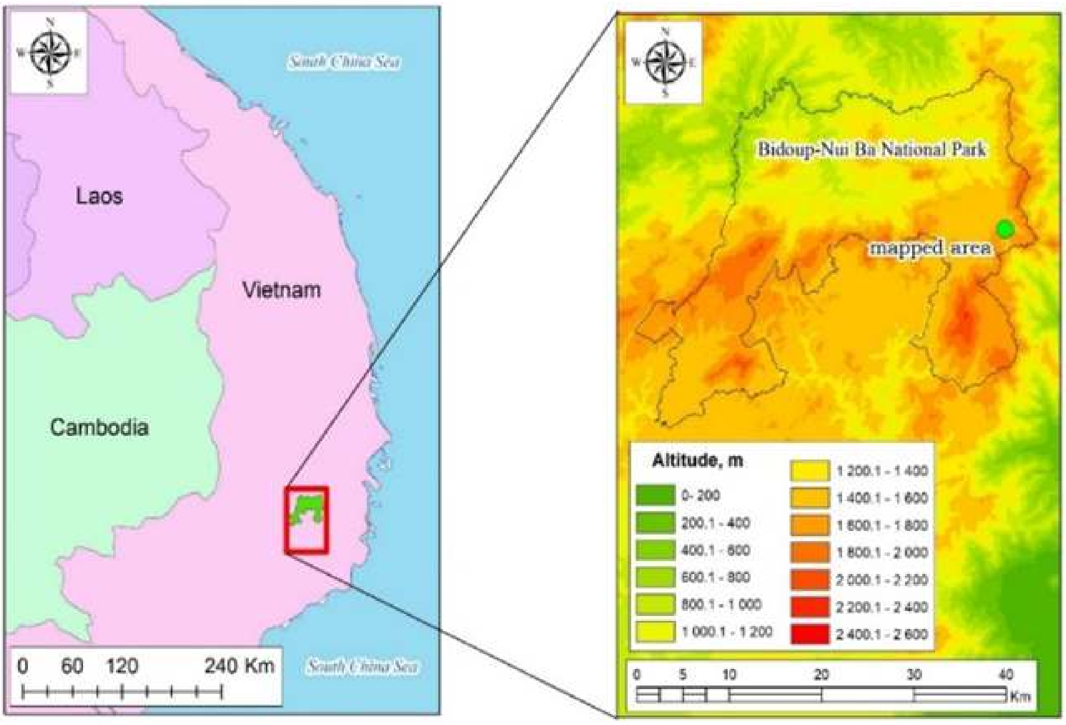

Figure 1. Map of the sampling area (Pham, 2024).

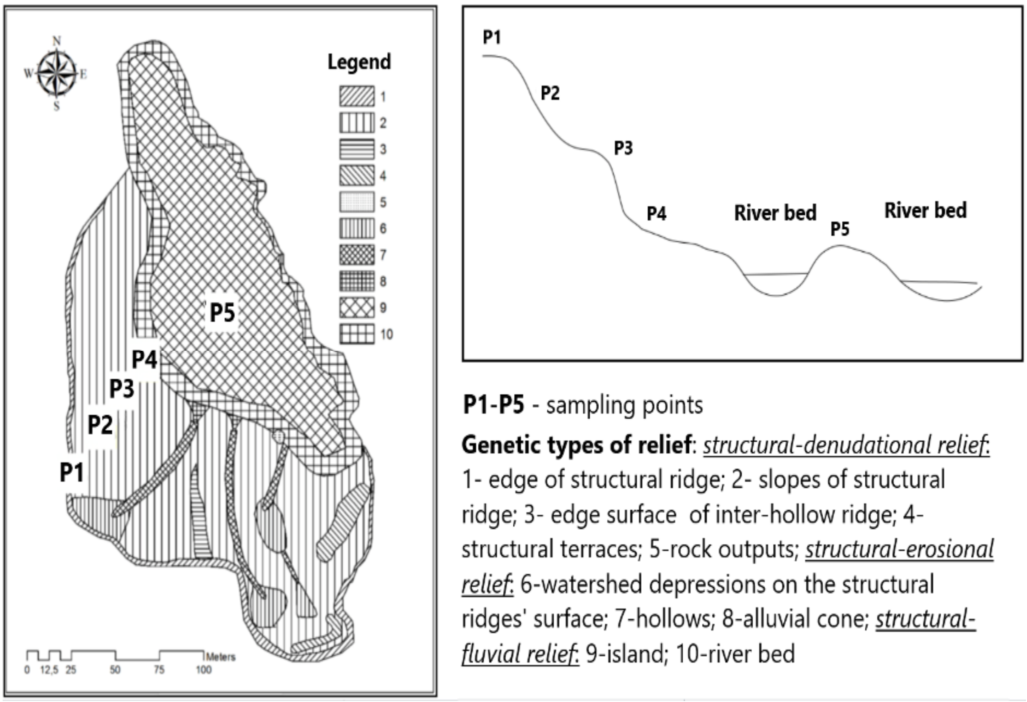

Figure 2. P1-P5 - soil profiles and sampling points of bamboo organs (Lebedev, 2019).

Characterization of soil sampling sites has the following criteria (Table 1).

The sampling and preparation of samples were carried out in accordance with GOST 17.4.4.02-84 (State Standard of the Russian Federation) (GOST, 2008). The sampling points for soil samples were selected, taking into account the wind rose and micro-relief features. According to the requirements of GOST, the organic soil horizon was sampled to a depth of 5 cm, where the majority of pollutants from the atmosphere usually accumulate (GOST 17.4.4.02-84, 2008). In accordance with the established methodology (Kidina, 2008), samples of above-ground plant parts were collected at the soil sampling locations.

The collected soil and plant samples were dried to an air-dry state. Soil sample weights were obtained through granulometric analysis using the sieving method. Dry ashing was used to determine the microelement content in the plants (Kidina, 2008). The total content of elements in soil and plant samples was determined according to PND F 16.2.2:2.3.71-2011 "Quantitative Chemical Analysis of Soils".

The determination of mobile forms of elements and heavy metals was carried out using a pH 4.8 acetate-ammonium buffer, following the methodological guidelines for determining heavy metals in agricultural soils and crop products (1992). The analysis of the soil and plant samples was carried out using a mass spectrometer with inductively coupled plasma, PlasmaQuant MS Elite S-NR:11-6000ST043, at the scientific and educational collaborative center "Spectrometry and Chromatography" at the Research Center of IBSS.

The degree of element availability in the soil in different landscape geochemical conditions was assessed using biogeochemical indicators: the coefficient of biological uptake (C_b) and the coefficient of biogeochemical mobility (C_m) (Avessalomova, 2007):

$$C_b = \frac{A}{S} \quad (1)$$

where:

C_b	=	coefficient of biological uptake
A	=	concentration of chemical elements in plant ash
S	=	concentration of the total form of this element in the rock or soil where the plant grows

$$C_m = \frac{I}{m} \quad (2)$$

where:

C_m	=	coefficient of biogeochemical mobility
I	=	concentration of a chemical element in a dry mass of a plant
m	=	concentration of active forms of this element in a rock or soil where this plant grows

To assess the overall intensity of microelement involvement in the biogeochemical cycle, the indicator of biogeochemical activity of the species in the involvement of microelements in the plant's biogeochemical cycle in a specific landscape is considered.

Results

Various exogenous processes have a complex influence on geochemical processes in soils. Due to the climatic characteristics of the territory, the most significant exogenous processes, including those related to relief formation, are biological, chemical, and physical weathering - slope processes of solifluction and defluction displacement, as well as valley erosion processes, whose activity prevents the formation of a thick layer of loose deposits, especially on slopes (Shishov, 1996). Soil profiles located in different landscape facies are characterized by corresponding dominant slope processes: automorphic (eluviated) conditions at the top of the ridge in P1, trans-eluviated conditions within the defluction slope in P2, and trans-accumulative conditions within the solifluction slope in P3. Due to the differences in landscape conditions, the studied organogenic horizons of the investigated soils were represented by At and A1 horizons of different thicknesses. The description of the studied horizons is presented in Table 1.

Table 1. Description of the organogenic horizons of the investigated points (Lebedev, 2019).

Point	Depth	Horizon Description
P1 At	0-12 cm	Color 5YR 1/3, loose, fresh, peat-like, structureless, powdery, consistency: weakly plastic, non-sticky, no new formations, no inclusions, living phase: small and medium plant roots D = 0.1-10 cm, smooth boundary, sharp transition in color and mechanical composition.
P2 At	0-5 cm	Color 7.5YR 1/2, loose, dry, peat-like, structureless and powdery, consistency: slightly sticky, non-plastic, no new formations, no inclusions, living phase: numerous plant roots D = 1 mm-1 cm, slightly undulating boundary, clear transition in color.
P3 A1	0-6/8 cm	Color 7.5YR 2/4, loose, fresh, heavy loam, fine to medium cloddy, consistency: non-sticky, non-plastic, no new formations, inclusions: numerous pebble inclusions, living phase: numerous small and medium plant roots D = 3-5 mm, slightly undulating boundary, clear transition in color.

In addition, the importance of seasonal moisture should be noted, as it directly affects the soil moisture regime, shifting from evaporation-dominated to leaching-dominated and vice versa. During the wet season, volumes of slope displacement of solid soil phase increase, volumes of plant litter translocation into coexisting landscape settings increase, and the rate of biogeochemical element migration in the "plant-litter-soil-plant" system significantly increases. To identify regional patterns of biogeochemical migration of microelements (Sheudzhenet et al., 2020), the chemical composition of soils and grass species (specifically bamboo) in the Bidoup-Nuibat Park was investigated.

Table 2 presents data on the content of total and mobile forms of elements in the soils of the study area at the end of the dry season. The decreasing order of the content of total and mobile forms in the humus horizons of the investigated soils is as follows: Mn > Zn > B > Mo > Cu > Co for point 1, Zn > Mn > B > Mo > Cu > Co for point 2, Mn > Zn > B > Mo > Cu > Co for point 3. Such variability in concentrations, apart from species-specific accumulation, may indicate different degrees of element availability in the soil under different landscape geochemical conditions. This can be inferred from biogeochemical indicators (C_b and C_m), which characterize the interrelationships in the "soil-plant" system.

Table 2. Content of total and mobile forms of microelements in the soil during the dry season, mg/kg.

Point/Horizon (t-total/m-mobile)		Elements					
		B	Mn	Co	Cu	Zn	Mo
P1/At	t	4.53	21.80	0.39	36.9	18.71	4.012
	m	0.99	14.23	0.035	0.32	6.88	0.004
P2/At	t	4.12	25.09	1.20	28.3	43.73	3.65
	m	1.31	22.89	0.28	1.25	28.32	0.01
P3/A1	t	5.55	26.61	1.95	30.9	11.33	3.43
	m	0.49	6.86	0.102	0.33	2.09	0.006

The chemical composition of plants is determined by the ecogeochemical conditions of their habitats, as well as by the selectivity and intensity of absorption of specific elements. Biological selectivity allows plants to control their chemical composition within certain limits (Nikonov et al., 2004). Differences in the accumulation of the studied elements in bamboo depend on their content in soils of landscape facies, as well as on the plant organ. The predominant accumulation of Cu in bamboo leaves and stems corresponds to its high content in the soils of the investigated facies. Zn and Mn selectively participate in the process of biological accumulation and do not have a direct dependence on their content in soils. The mobility and accumulation (C_m and C_b) of the total form of B in bamboo stems correlate with its content in the organogenic horizons of the investigated soils, while its accumulation (C_b) in bamboo leaves is inversely proportional to its content in soils. However, the migratory mobility (C_m) of the labile form of B in bamboo leaves correlates with its content in the organogenic horizons of the investigated soils. Certain patterns were also identified for Mo and Co. The accumulation (C_b) of Mo in bamboo leaves correlates with the content of mobile forms of Mo in soils, while the Cm of Mo in bamboo leaves and stems correlates with the content of its total forms in the organogenic horizons of the investigated soils. For the content of Co in soils and plant organs, opposite trends of accumulation were observed: the C_b of Co in bamboo leaves correlates with the content of mobile forms of Co in soils and is inversely proportional to the content of total forms. Additionally, the C_b of Co in stems is inversely proportional to the content of its mobile forms in the investigated soils. The mobility of Co (C_m) in bamboo leaves and stems is inversely proportional to the content of its mobile forms in soils. The coefficients of biological absorption (C_b) presented in Table 3 indicate the potential ability of bamboo organs to absorb elements and accumulate them in different landscape facies. In the autonomic facies, the C_b of leaves is higher than the C_b of stems for all elements (highlighted in bold), except for Zn. In the trans-eluvial facies, the C_b of leaves is higher than the C_b of stems for all investigated elements.

In contrast, in the trans-accumulative facies, the C_b of stems is higher than the C_b of leaves for all elements. It is noted that the C_b values of leaves (for Mn and Zn) and stems (for Cu) consistently decrease from the autonomic to the trans-accumulative facies (highlighted in gray). Overall, in the autonomic facies, there is an accumulation (C_b>1) of Mn in leaves and Mn and Zn in stems. In the trans-eluvial facies, there is an accumulation of B and Mn in leaves, while no element accumulation is detected in stems. In the trans-accumulative facies, no accumulation is observed in leaves, but Mn accumulates in bamboo stems.

Table 3. Coefficient of biological absorption of elements in bamboo leaves and stems (C_b) and coefficient of biogeochemical mobility (C_m) during the dry season.

		P1		P2		P3	
		Leaves	**Stems**	**Leaves**	**Stems**	**Leaves**	**Stems**
B	C_b	**0.93**	0.49	**1.43**	0.25	0.22	**0.41**
	C_m	**4.24**	2.23	**4.47**	2.06	2.42	**4.65**
Mn	C_b	**5.26**	3.36	**3.14**	0.68	0.74	**1.62**
	C_m	**8.06**	5.15	**3.44**	2.49	2.86	**6.29**
Co	C_b	**0.13**	0.10	**0.12**	0.03	0.01	**0.04**
	C_m	**1.49**	1.15	**0.50**	0.30	0.73	**1.56**
Cu	C_b	**0.16**	0.15	**0.50**	0.13	0.03	**0.06**
	C_m	**17.92**	17.35	11.29	**11.34**	3.16	**5.39**
Zn	C_b	0.98	**4.87**	**0.69**	0.21	0.19	**0.55**
	C_m	2.65	**13.23**	1.06	**4.29**	1.05	**3.00**
Mo	C_b	**0.02**	0.01	**0.04**	0.01	**0.01**	**0.01**
	C_m	**14.16**	7.54	**13.22**	5.83	3.62	**4.12**

The coefficient of biogeochemical mobility (Table 3) indicates the actual intensity of element biouptake. Bamboo, like many plants, is an active bioaccumulating species for mobile elements such as B, Mn, Co, Cu, Zn, and Mo (C_m>1). The Cm values of bamboo leaves and stems correspond to the C_b values for the facies, except for the trans-eluvial facies, where the C_b and C_m of leaves and stems show inverse accumulation patterns for Cu and Zn. In the autonomic facies, there is an accumulation (C_m >1) of all elements in both leaves and stems. In the trans-eluvial facies, there is an accumulation of B, Mn, Cu, Zn, and Mo in both leaves and stems. In the trans-accumulative facies, there is an accumulation of B, Mn, Cu, Zn, and Mo in leaves and an accumulation of all elements in bamboo stems. It is noted that the Cm values in leaves (for Mn, Zn, Mo) and in stems (for Cu, Zn, and Mo) consistently decrease from the autonomic to the trans-accumulative facies (highlighted in light gray). The content of total and mobile forms of elements in the soils of the investigated area at the end of the wet season is presented slightly differently. The data for the organogenic horizons are provided in Table 4. The decreasing order of content for total and mobile forms in the humus horizons of the studied soils is as follows: Zn > Mn > B > Cu > Co > Mo for point 1, and Zn > Mn > Cu > B > Co > Mo for points 2 and 3. We observed that the content of the investigated elements in the organogenic horizons of soils changes by the end of the wet season. Despite the prevailing content of Zn in the soils, its accumulation in the organs of green plants significantly lags behind Cu, which may indicate the toxic properties of Zn. The predominant accumulation of Cu and Mn in the leaves and stems of bamboo corresponds to their high content in the soils of the studied facies. Despite the substantial difference in soil content (B > Mo), both elements are actively accumulated in the organs of bamboo. The content of Co in the soils is inversely proportional to its accumulation in the organs of bamboo. The coefficients of biological absorption (C_b) presented in Table 5 indicate the potential ability of bamboo to absorb elements and accumulate them in its organs in different landscape facies. In the autonomic facies, the C_b of leaves is higher than the C_b of stems for all elements (highlighted in bold) except for Zn. In the trans-eluvial facies, the C_b of leaves is higher than the C_b of stems for all investigated elements. In the trans-accumulative facies, the C_b of leaves is higher for B, Mn, and Co, while for Cu, Zn, and Mo, it is higher for stems. It is worth noting that the C_b of bamboo leaves increases in relation to B, Cu, and Zn from the autonomic to the trans-accumulative facies (highlighted in light gray), while this pattern is not observed for the C_b of bamboo stems. Overall, in the autonomic facies, there is an accumulation (C_b >1) of Mn and Cu in leaves and Mn, Cu, and Zn in stems; in the trans-eluvial facies, there is an accumulation of B, Mn, Cu, Zn, and Mo in leaves, and Mn in stems; in the trans-accumulative facies, there is accumulation of B, Mn, Co, Cu, Zn in leaves, and all elements in bamboo stem.

Table 4. Content of total and mobile forms of trace elements in the soil during the wet season, mg/kg.

Point/Horizon (t-total/m-mobile)		B	Mn	Co	Cu	Zn	Mo
P1/At	t	5.79	13.52	0.47	5.12	29.22	0.099
	m	0.31	3.46	0.068	0.20	5.91	0.009
P2/At	t	4.62	16.54	1.68	4.86	27.92	0.10
	m	0.28	5.182	0.25	0.23	6.06	0.013
P3/A1	t	3.91	11.044	0.45	6.00	12.37	0.096
	m	0.27	4.53	0.11	0.35	2.20	0.008

Table 5. Coefficient of biological absorption of trace elements by bamboo (C_b) and coefficient of biogeochemical mobility (C_m) during the wet season.

		P1		P2		P3	
		Leaves	Stem	Leaves	Stem	Leaves	Stem
B	C_b	**0.73**	0.38	**1.28**	0.22	**24.03**	13.74
	C_m	**13.44**	7.06	**20.62**	3.56	**338.64**	193.58
Mn	C_b	**8.47**	5.42	**4.76**	1.03	**80.62**	65.91
	C_m	**33.05**	21.14	**15.20**	3.29	**196.54**	160.67
Co	C_b	**0.11**	0.08	**0.08**	0.02	**3.72**	3.36
	C_m	**0.76**	0.59	**0.56**	0.12	**15.16**	13.69
Cu	C_b	**1.12**	1.08	**2.91**	0.79	4.21	**7.19**
	C_m	**28.44**	27.54	**60.68**	16.36	72.04	**122.87**
Zn	C_b	0.62	**3.11**	**1.08**	0.32	2.21	**7.39**
	C_m	3.08	**15.39**	**4.96**	1.48	12.44	**41.48**
Mo	C_b	**0.70**	0.37	**1.38**	0.34	0.72	**2.06**
	C_m	**7.53**	4.01	**10.33**	2.53	7.59	**22.73**

The coefficient of biogeochemical mobility (C_m) indicates the actual intensity of element biouptake, as shown in Table 5. Bamboo, like many plants, is an active bioaccumulating species for mobile elements such as B, Mn, Co, Cu, Zn, and Mo (C_m >1). The Cm values of bamboo leaves and stems correspond to the Cb values for the facies. In the autonomic and trans-eluvial facies, there is accumulation (C_m >1) of B, Mn, Cu, Zn, and Mo in both leaves and stems. In the trans-accumulative facies, there is an accumulation of all elements in the leaves and stems of bamboo. It is noted that the Cm values in leaves (for B, Cu, Zn) consistently increase from the autonomic to the trans-accumulative facies (highlighted in light gray).

Discussion

The variability in soil chemical element concentrations can be attributed to factors such as weathering, soil formation processes, and the original geological material. This variability is also observed across different plant species growing in identical environments. The divergences in these findings could stem from the distinct nutritional needs and element absorption mechanisms inherent to each plant species. These differences manifest in the unique physiological, biochemical, and metabolic functions of the plants, as noted by Phuong (2013).

Table 6 details the chemical element content found in the soils of several national parks across Vietnam. This research was limited to the trace elements manganese (Mn), copper (Cu), and zinc (Zn), consistent with the focus on heavy metals in Vietnamese soil studies, including those at Bidoup-Nui Ba National Park. The levels of these trace elements detected in our investigation are consistent with the ranges reported in other studies within Vietnam's national parks.

Table 6. Comparison of trace element contents in soils of different regions (mg/kg).

Region	**Bidoup-Nui Ba National Park**	**Cat Tien National Park**	**Con Chu Rang National Park**	**Bidoup-Nui Ba National Park**	**York Don National Park**	**Bu Gia Map National Park**	**Kon Ka Kinh National Park**
References	This study	Nguyen and Okolelova (2015)	Nguyen and Okolelova (2017)	Do (2022)	Do (2022)	Do (2022)	Nguyen and Okolelova (2017)
B	4.53						
Mn	21.80			8.36-14.97		168.76-530.4	
Co	0.39						
Cu	3.69	46.9	19.12-31.58	1.05-32.51	4.24-79.03	47.44-61.53	23.20-37.55
Zn	18.71	210		9.08-52.05		48.09-109.31	29.936-100.10
Mo	4.012						

Our examination of trace element levels in organogenic soil layers during both wet and dry seasons, as outlined in Tables 2 and 4, revealed distinct trends and allowed us to evaluate the impact of soil moisture on the migration, biological mobility, and accumulation of these elements. The end of the wet season, marked by increased litterfall and branch loss, leads to a notable buildup of these elements in organogenic layers. This process alters the sequence in which the total and mobile forms of the elements decrease. Under autonomic conditions (point 1), the sequence is as follows: for the dry season, Mn > Zn > B > Mo > Cu > Co, and for the wet season, Zn > Mn > B > Cu > Co > Mo. In trans-eluvial environments (point 2), the order is Zn > Mn > B > Mo > Cu > Co for the dry season and Zn > Mn > Cu > B > Co > Mo for the wet season. Under trans-accumulative conditions (point 3), the sequences are Mn > Zn > B > Mo > Cu > Co for the dry season and Zn > Mn > Cu > B > Co > Mo for the wet season.

During the wet season, there is a significant influx of Zn, Cu, and Co due to plant litterfall, which contrasts with Mo, which tends to accumulate in the dry season. Mn and B show year-round accumulation, but the highest Mn levels are linked to the dry season, correlating with its reduced migration activity that relies on adequate soil moisture—neither too little nor excessive. B's content is also influenced by soil moisture; it accumulates under autonomic and trans-eluvial conditions when moisture is ample during the wet season, whereas in the dry season, such conditions are more likely under trans-accumulative scenarios. Conversely, the wet season sees reduced B accumulation due to the surface runoff and leaching of organic matter.

Bamboo, with its various components like roots, rhizomes, stems, branches, leaves, and shoots, exhibits differential heavy metal concentrations across its tissues, with roots often showing higher levels (Bian, 2020). Recognized for its phytoremediation potential, bamboo is resilient to heavy metal-rich soils and can amass significant biomass (Chen et al., 2015; Liu et al., 2015). Each bamboo organ has a unique capacity for absorbing and storing chemical elements. Bamboo leaves, in particular, are adept at taking up trace elements from both soil and atmospheric deposits, leading to elevated element concentrations in foliage compared to subterranean parts of the plant (Bagdatlioglu et al., 2010; Milicevic et al., 2018). In Vietnam, research on the biological uptake of trace elements by plants, especially bamboo, has been scarce. Our study aimed to bridge this gap by comparing our findings with data from other global regions where bamboo thrives. The literature predominantly explores various bamboo species' abilities to accumulate metals like Cu, Zn, Mn, Fe, Cr, Cd, and Ni.

In their investigation of naturally contaminated environments, Bian et al. (2017) discovered that in Moso bamboo, copper (Cu) was most abundant in the roots, followed by rhizomes, leaves, branches, and stems. Zinc (Zn), on the other hand, was primarily found in branches and leaves, with the smallest amounts in rhizomes. Duan et al. (2019) reported that for *Fargesia denudata*, the leaf-to-stem Cu ratio was 3.0, while for *F. robusta*, it was significantly lower at 0.2 and 0.1. A similar pattern was observed for Zn. In the same study on Moso bamboo, the leaf-to-stem Cu ratio was higher in leaves (0.26) than in stems (0.17), and a comparable trend was seen for Zn (0.52 in leaves vs. 0.44 in stems).

These findings are consistent with our research, where the leaf-to-stem ratios for Cu and Zn were generally higher in leaves, except for Zn during the autonomic and trans-accumulative phases and for Cu in the trans-accumulative phase, where the ratios were inverted. For other elements, the leaf-to-stem ratios were predominantly higher in leaves: in the autonomic phase, all elements except Zn; in the trans-eluvial phase, all elements; and in the trans-accumulative phase, B, Mn, and Co, while for Cu, Zn, and Mo, the ratios were higher. Our study found that the leaf-to-stem ratios for Cu and Zn in Bambusoideae were greater than those in other bamboo species like *Fargesia denudata*, *F. robusta*, and Moso bamboo, with ranges of 1.12 to 4.21 for Cu and 0.79 to 7.19 for Zn in leaves and stems. Shukla et al. (2011) highlighted that *Dendrocalamus strictus* had a high potential for accumulating Mn and Zn, more so than other woody plants like *Terminalia arjuna, Prosopis juliflora*, *Populus alba*, and *Eucalyptus tereticornis*.

Our study extended beyond assessing bamboo's capacity to accumulate trace elements; we also explored how this capacity fluctuated with the seasons and across different landscape positions. We noted varied trends in the accumulation and biogeochemical migration of mobile forms of elements, which seemed closely linked to soil moisture. This will be further examined in our analysis of biological absorption (C_b) and biogeochemical mobility (C_m). During the wet season, we observed a reduction in the mobile forms of B, Mn, Cu, and Zn in the soil of the studied landscape facies. However, this trend did not hold for Cu and Zn under trans-accumulative conditions, likely due to the lateral migration of soil solutions from adjacent landscape facies. Conversely, we saw an increase in the labile forms of Co under autonomic and trans-accumulative conditions, while a slight decrease occurred in trans-eluvial conditions due to migration to lower landscape facies. The wet season also brought an increase in the labile forms of Mo, along with a decrease in its total form, suggesting its involvement in migration processes facilitated by moisture and the influx of organic acids from heavy rainfall.

The biogeochemical mobility (C_m), as shown in Tables 3 and 5, was significantly higher during the wet season. We recorded substantial increases in C_m for Cu (1.6-22 times in leaves and stems), Mn (4-68 times in leaves and 1.3-25 times in stems), and B (3-140 times in leaves and 1.7-40 times in stems), indicating their active participation in biogeochemical cycles influenced by soil moisture. The increase in C_m for B progressed from autonomic to trans-accumulative conditions in both leaves and stems, while for Cu, it was observed only in leaves. No such pattern was found for Cu in stems or Mn in both leaves and stems, which presents an interesting area for future study. A direct correlation was noted between the biogeochemical mobility of Zn and its total and mobile forms in the soil. During the wet season, under autonomic conditions, a rise in soil Zn levels led to increased C_m but reduced biological accumulation, particularly in bamboo stems. In trans-eluvial conditions, a drop in soil Zn concentration boosted its biological uptake by bamboo leaves. In trans-accumulative conditions, a slight rise in soil Zn content, possibly from adjacent landscape facies, resulted in both heightened C_m (12 and 14 times for leaves and stems, respectively) and significant biological accumulation (11 and 13 times for leaves and stems, respectively), hinting at the toxic effects of high Zn levels in soil on plant tissues. Mo showed active involvement in migration during the wet season, moving to adjacent landscape facies from autonomic conditions. A transition of Mo into more labile forms led to reduced biogeochemical mobility and increased biological absorption (a decrease in total Mo content in soil). The behavior of Co was less clear and merits further investigation. Under trans-accumulative conditions, a marked increase in C_m for Co was observed, with a 20- and 8-fold rise for leaves and stems, respectively. However, under autonomic and trans-eluvial conditions, biogeochemical mobility decreased.

Conclusion

The study conducted provided insights into the elements most actively involved in biogeochemical migration and accumulation during the wet and dry seasons. It evaluated the biogeochemical mobility of elements and the intensity of biological accumulation in bamboo organs across different landscape conditions throughout these seasons. This analysis helped to delineate the nuances of trace element biogeochemical migration within the "soil-plant" system of Bidoup-Nui Ba National Park's coexisting landscape facies during both wet and dry periods.

The uptake of microelements by plants was found to be influenced by the landscape facies where the soil is situated and the prevailing moisture conditions, whether during the wet or dry season, within the organogenic soil horizons. Zn, Cu, and Co were introduced into the soil via plant litter during the wet season, leading to their accumulation. Conversely, Mo predominantly accumulated during the dry season, while Mn and B were noted to accumulate consistently throughout the year. A general decrease in the mobile forms of B, Mn, Cu, and Zn was observed in the soils of the studied landscape facies during the wet season.

Biological uptake by bamboo organs, such as leaves and stems, was found to vary depending on the landscape facies in which they grew and the season. Under autonomic conditions, Mn and Zn (only in stems) accumulated throughout the year, with Cu also accumulating in both leaves and stems during the wet season. In trans-eluvial conditions, Mn and B (in leaves) accumulated year-round, with additional uptake of Cu, Zn, and Mo in leaves during the wet season. Under trans-accumulative conditions, Mn (in stems) accumulated throughout the year, with B, Mn, Co, Cu, Zn in leaves and B, Mn, Co, Cu, Zn, Mo in stems accumulating during the wet season.

The biogeochemical mobility (C_m) of elements in bamboo organs was found to increase significantly with soil moisture during the wet season. Compared to dry season values, there was a substantial rise in C_m for Cu (1.6-22 times for leaves and stems), Mn (4-68 times for leaves and 1.3-25 times for stems), and B (3-140 times for leaves and 1.7-40 times for stems).

The research uncovered several peculiarities in the accumulation and biogeochemical migration of the elements studied. An increase in B accumulation was linked to soil moisture, while its decrease was associated with intensified slope processes during the wet season. Additionally, the migratory mobility (C_m) of labile B forms in bamboo leaves correlated with their content in the organogenic soil horizons. The increase in C_m for B in leaves and stems occurred sequentially from autonomic to trans-accumulative conditions, while Cu showed a direct correlation in leaves. A direct relationship was observed between the biogeochemical mobility and the content of total and mobile forms in the soil for Zn (C_m). The C_m of Mo in bamboo leaves and stems was linked to its content in the total forms in the soil. The mobility of Co (C_m) in bamboo leaves and stems was inversely related to the content of its mobile forms in the soil. During the dry season, C_m values for Mn, Zn, and Mo in leaves, as well as Cu, Zn, and Mo in stems, decreased sequentially from autonomic to trans-accumulative conditions. In contrast, during the wet season, C_m values for B, Cu, and Zn in leaves increased sequentially from autonomic to trans-accumulative conditions. Interestingly, the position of coexisting landscape facies did not significantly impact C_m values for Cu and Mn in bamboo stems, presenting an intriguing topic for future research.

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