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Tree ring δ^{13}C of *Pines* at acidic soil forest in central Vietnam: A preliminary result for further stable isotope application on climate change and environmental protection

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ABSTRACT

This case study evaluates an innovative methodological approach that integrates soil chemical analysis (including pH, organic matter, total nitrogen, and grain size composition) with tree-ring δ^{13}C measurements to assess long-term forest soil acidification processes. The study was conducted in Nang Pine Forest, located in Phong Nha-Ke Bang National Park, central Vietnam. Soil grain size analysis reveals a predominance of fine particles over coarse particles. There is a difference in the distribution of soil components at depth. The results indicate that the soil tends to be acidic, with a low pH that increases in depth, while it contrasts with the total nitrogen content. This acidity may result from natural processes and human activities, such as the release of acid rain. The findings also highlight the influence of topography and climate on soil properties.

Furthermore, soil pH was negatively correlated with δ^{13}C in pine tree rings in central Vietnam. This relationship could serve as a valuable tool for assessing past soil degradation processes, reconstructing historical environmental changes, or analyzing the connection between δ^{13}C content in pine tree rings and climate change in the region. The results suggest that mitigating soil acidity and supporting healthier tree growth are essential to improve soil pH through the planting of suitable tree species and effective vegetation management in the study area. This study's integrated approach provides both current assessments and historical reconstructions, establishing a replicable and cost-effective methodological framework applicable to other tropical forest ecosystems under acidification stress. This framework provides valuable insights to advance both research and conservation management.

Keywords: Acidification, soil pH, tree ring δ^{13}C, pine forest.

1. Introduction

Natural forests are crucial for conserving biodiversity, protecting the environment, promoting socio-economic development, and ensuring the livelihoods of forest-dependent communities (Stibig et al., 2007; Dinh and Vinh, 2021). In particular, forest land, with its significant carbon storage capacity, plays a key role in maintaining ecological balance and mitigating climate change (Lal, 2004; Li et al.,

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2017; Zhou et al., 2019; FAO, 2001, 2006). However, soil acidification threatens forest ecosystems by degrading soil quality, hindering tree growth, and destabilizing the ecological environment (Nagy and Konya, 2007; Russbelt et al., 2024). This process is accelerated by acid rain, air pollution, and nitrogen deposition from industrialization (Miller and Watmough, 2009; Tomlinson, 2003; Chen et al., 2010). Numerous studies have shown that prolonged acid deposition is a major driver of forest degradation (Schulze et al. 1989; Tamm and Hallbacken, 1988), while nitrogen deposition from industrial activities accelerates soil acidification, posing a global threat to forest ecosystems (Ito et al., 2011; Šantrůčková et al., 2007; Sverdrup et al., 1996). Given the spatial variability of soil pH, precise measurement and control are essential for maintaining forest stability and promoting sustainable development.

Research methods for soil degradation, especially soil acidification, have been applied through various approaches, from direct measurements of soil chemical indices (e.g., pH, exchangeable cations, sulfate, and nitrate concentrations) (Meng et al., 2019; Tian and Niu, 2015; Goulding, 2016) to field surveys, long-term experiments (Li et al., 2019; Zhu et al., 2024; Guo et al., 2010), and modeling (Zhu et al., 2024; Dong et al., 2022; Hao et al., 2022). These traditional methods offer advantages such as relative simplicity, low cost, and the ability to provide instantaneous indicators of soil health, but also have significant limitations, such as the lack of reliable data and accurate assessment criteria (Lal, 2015; Ferreira et al., 2021), few practical field screening tools (Saljnikov et al., 2021; Meng et al., 2019; Tian and Niu, 2015), and these methods mainly reflect current rather than historical developments, while acid deposition data series are often only recent. In addition, relying solely on indicators such as pH may overlook other important aspects of soil quality, including nutrients, organic matter, and biological activity (Meng et al., 2019; Tian and Niu, 2015; Wang and Kuzyakov, 2024). Recent studies have extended to kinetic modeling (DeWalle et al., 2003; Hopf et al., 2023), chemical characterization and buffering capacity (Huang et al. 2009), spatial analysis and VSD modeling (Boruvka et al., 2005; Čakmak et al., 2014), as well as artificial intelligence applications (Zamanian et al., 2024) to predict acidification dynamics. However, these methods are often resource-intensive, sensitive to seasonal fluctuations, and have limited ability to capture long-term variability.

In this context, the use of tree-ring $\delta^{13}C$ data in environmental and ecological studies has attracted considerable attention, with recent studies exploring its potential in understanding soil properties, including soil pH (Viet et al., 2013). However, the primary focus of many studies has been on water use efficiency, drought response, and climate reconstruction (Hartl-Meier et al., 2015). Previous studies have demonstrated that tree growth rings are valuable tools for deciphering historical environmental changes, particularly the effects of soil acidification on tree growth (Savard, 2010; Choi and Lee, 2012). Stable isotope analysis of tree rings allows researchers to investigate the relationship between environmental conditions and plant function by understanding the dynamics of isotopic fractionation (Dawson et al., 2002; Siegwolf et al., 2021). Carbon (C) isotopes in tree rings have been widely used to study atmospheric changes, reflecting CO_2 increases due to organic matter decomposition, fossil fuel combustion, and the presence of pollutants such as SO_2, NO_x, and O_3 (Kwak et al., 2009, 2011; McCarroll et al., 2009; Siegwolf et al. 2001; Choi and Lee, 2012). Previous studies have demonstrated that soil acidification directly affects the ^{13}C isotope ratio in plants

(Savard, 2010; Viet et al., 2013). Acid rain decreases $\delta^{13}C$ by inhibiting carboxylation due to chlorophyll damage (Shan, 1998; Kwak et al. 2009), while nitrogen deposition can increase $\delta^{13}C$ by activating photosynthetic enzymes, thereby influencing plant growth (Choi et al., 2005). Viet (2013) found that plants growing in low-pH soils tend to have poor development, indicating the severe impact of soil acidification on plant health. Since soil acidification is a slow, long-term process, its effects result from chronic exposure rather than acute toxicity (Ito et al. 2011). Therefore, tree-ring analysis can monitor long-term environmental changes by integrating ecological impacts over time and preserving annual information on physiological responses to soil conditions. It also enables the assessment of the mechanisms and extent of soil acidification impacts on forest ecosystems. This approach can overcome the limitations of traditional methods for investigating soil degradation processes.

Recent climate changes are widespread, rapid, and increasingly strong in almost every region on Earth (Vu, 2021; Hoang-Cong et al., 2022). Given the increasing risks of climate change and desertification in Central Vietnam, understanding soil chemical processes is essential for mitigating adverse impacts on forest resources and the regional ecosystem. This study aims: (1) to investigate characteristics of the study area soil relating different soil from randomly collected samples; (2) to study the relationship between soil acidity and the carbon isotopic composition ($\delta^{13}C$) in the tree rings of pines at different ages; and (3) to explore the potential of tree-ring $\delta^{13}C$ as a bioindicator by correlating it with soil pH, thereby contributing to early insights into soil degradation processes at different ages at the Nang pine forest, located within the Phong Nha-Ke Bang Nature Reserve, Quang Binh, Central Vietnam. By applying a case study approach, this study aims to provide baseline data and methodological insights to inform larger-scale investigations of land degradation and forest ecosystem responses under changing environmental conditions.

2. Subjects and methods

2.1. Natural characteristics and sampling

Quang Binh is a North Central coastal province that holds a vital position in Vietnam's national economy, defense, and security. The province boasts a diverse range of terrains, including forests, beaches, and numerous scenic natural landscapes. Additionally, it possesses various mineral resources with high economic value. Due to its geographical location, Quang Binh is influenced by both winter and summer monsoons, as well as maritime and continental air masses. Furthermore, the province's complex topography, dense river and stream networks, short river lengths, steep slopes, and challenging climatic and hydrological conditions all contribute to the occurrence of extreme weather events. Hot temperatures, storms, floods, and severe cold spells occur almost annually, posing significant challenges to local socio-economic development.

The Nang Pine Forest in Phong Nha-Ke Bang Nature Reserve, Quang Binh, is an ecologically significant area increasingly affected by soil acidification due to acid rain and other environmental factors. Vietnam is considered a country significantly affected by climate change, with extreme weather events (Thanh et al., 2022; Minh and Duy, 2022; Ngo-Duc, 2023; Pham-Thanh et al., 2024). Central Vietnam frequently experiences floods, erosion, and the impacts of climate change, making its soils vulnerable to degradation and reducing their water retention capacity and nutrient availability (Tran et al., 2010; Nguyen et al., 2023). Coniferous trees, such as pines, are ideal subjects for environmental, climatological, and ecological research due to their widespread distribution and clearly defined growth rings (Battipaglia et al., 2009; Sass-Klaassen et al., 2008). Growth ring analysis in conifers provides high-resolution and precise data, facilitating long-term environmental monitoring.

The Nang pine (Podocarpus imbricatus Bl.), also known as Bach Tung, Chicken Feather Pine, May Incense, Savat, Songo, Nori, Tran, Ngo Ri, Sri, Vra Pint, Ca Do, and Ori, belongs to the Podocarpaceae family (VAST, 2007). It is a large-sized tree with a round, evenly shaped trunk. Sampling points for this study were located in the Nang Pine Forest within Phong Nha-Ke Bang National Park, covering the communes of Tan Trach, Thuong Trach, Phuc Trach, Xuan Trach, and Phong Nha Town in Bo Trach District, Quang Binh Province (Fig. 1).

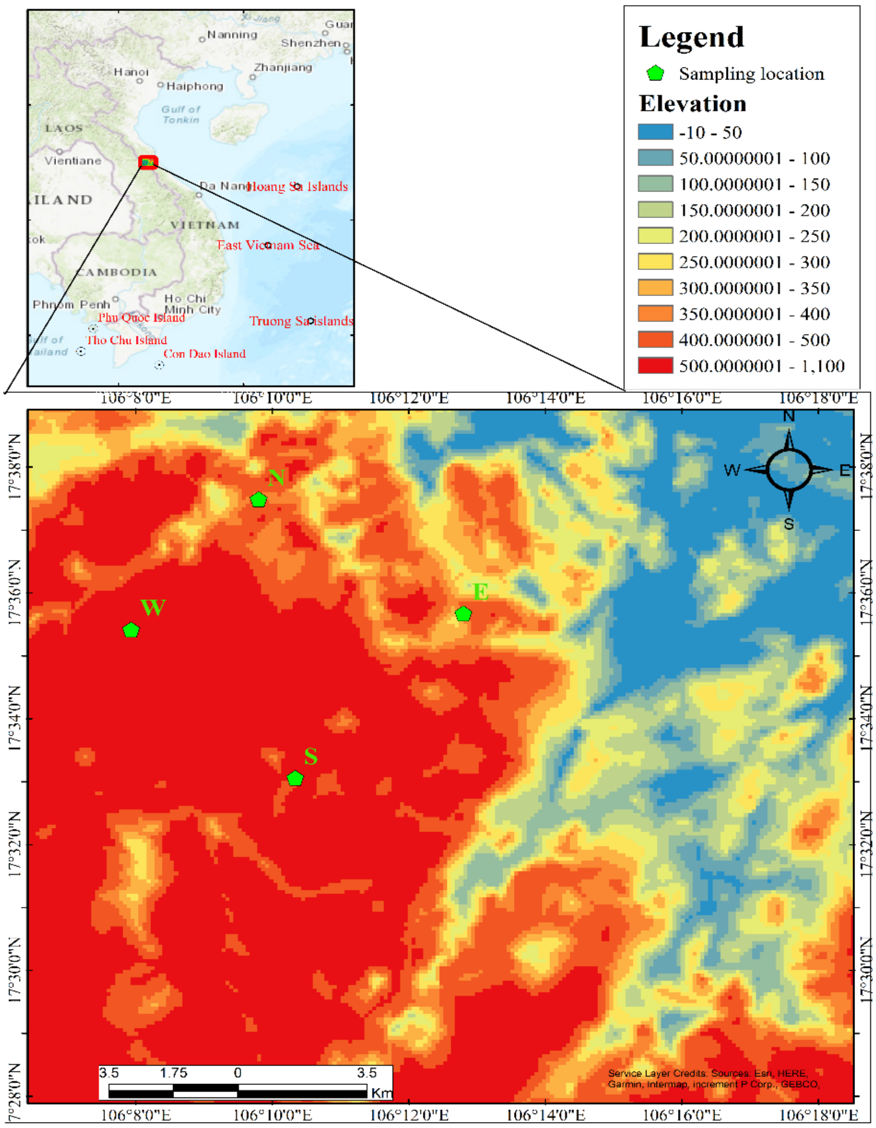

Figure 1. The map of the study area

Representative soil samples were collected from four locations: N (X: 106.163; Y: 17.6248), E (X: 106.213; Y: 17.5946), S (X: 106.172; Y: 17.5510), and W (X: 106.132; Y: 17.5903). At each location, samples were taken from four points positioned at the corners of a 9 m² square surrounding the study pine trees. Soil was collected at three depth intervals: 0–20 cm, 20–50 cm, and 50–100 cm, based on soil color and physical characteristics. The surface layer (0–20 cm) was primarily influenced by vegetation cover, rainfall, and surface water, whereas the deeper layers exhibited uniform coloration, consistent with the stratigraphy of the pine forest. To enhance analytical representativeness, samples from the same depth and physical characteristics were combined, resulting in 12 samples being selected for laboratory analysis. These samples were stored in labeled plastic bags and analyzed for soil particle composition, pH, total organic matter (OM), and total nitrogen. The sampling, preprocessing, and storage procedures followed the National Standard TCVN-7538-6:2010 on Soil Quality, ensuring methodological consistency and data reliability.

2.2. Grain size analyses

Grain size composition was determined following the National Standard TCVN-8567:2010. A 20 g soil sample was sieved through a 0.20 mm filter to remove organic particles larger than 0.5%. The processed and dried sample was then treated with 20 ml of dispersing solution and left to soak overnight. Subsequently, the sample was transferred to a beaker or bottle, diluted to a total volume of 250–300 ml with water, and subjected to dispersion. This was achieved either by stirring at high speed for 10 minutes or by shaking for 16 hours using a circular motion device. The resulting suspension was then analyzed to determine grain size composition.

2.3. pH, total nitrogen, and organic carbon content measurement

Soil pH was measured using a glass electrode in a 1:5 (volume fraction) soil-to-water suspension, following TCVN-5979:2007 (ISO-10390:2005). A 5 g soil sample was mixed with 25 ml of KCl solution (1 mol/L), shaken for 30 minutes to create a suspension, and left to stabilize for 2 hours. The pH of the suspension was then measured using a pH meter at a temperature of approximately 20°C.

Total nitrogen content (%N) was determined using the modified Kjeldahl method (National Standard TCVN-6498:1999). A 1 g soil sample was digested with H_2SO_4, sodium thiosulfate, and a catalyst until the solution was clear. The digest was then distilled with boric acid and NaOH, and the resulting condensate was titrated with H_2SO_4 to a purple endpoint. A blank test was conducted to ensure accuracy.

The organic carbon content (OC%) was determined using the Walkley-Black method, as specified in TCVN-8941:2011. This standard specifies the determination of total organic carbon in soil using the wet oxidation process with potassium dichromate ($K_2Cr_2O_7$) in sulfuric acid (H_2SO_4). A 0.2–0.5 g soil sample was weighed, mixed with 10 mL of $K_2Cr_2O_7$ solution, and then combined with 20 mL of H_2SO_4. The mixture was allowed to cool for 30 minutes before 100 mL of H_2O was added to cool it completely. Next, 10 ml of H_3PO_4 and three drops of ferroin indicator were added, and the solution was titrated with Mohr's salt solution.

2.4. Delta ^{13}C of tree ring sample

A Haglöf increment borer (Sweden) with a 5 mm drill bit diameter and 70 cm length was used to extract tree cores for determining tree-ring width (TRW) and age. Tree core sampling was conducted at 1.3 meters above ground level, following established dendrochronological methods (Fritts et al., 1969; Stokes et al., 1996). Twelve tree core samples were collected for timing; these samples were also selected for carbon isotope ($\delta^{13}C$) analysis. $\delta^{13}C$ values were calculated as the mean for 20-year, 100-year, and 200-year intervals, relative to the year 2023, based on 10-year climate variability cycles (Kwak et al., 2016). Regarding the physical mechanism, through software CDendro 7.3, ring width and area are responsible for accurately reflecting the tree's physical characteristics. Two hundred rings from the year 1825 to the present have been used for research.

Carbon isotope compositions (δ) were calculated as (Criss, 1999):

$$\delta(‰) = \left[\frac{R_{sample}}{R_{standard}} - 1 \right] \times 1000$$

The standards were Vienna-Pee Dee Belemnite (VPDB) (1.12372 atom%) for C. Multiple (n = 3) replicate analyses of an internal working standard (Pine wood with −26.7±0.1‰ of $\delta^{13}C$) indicated that the standard deviations for $\delta^{13}C$ measurements were < 0.3‰ (Fig. 2).

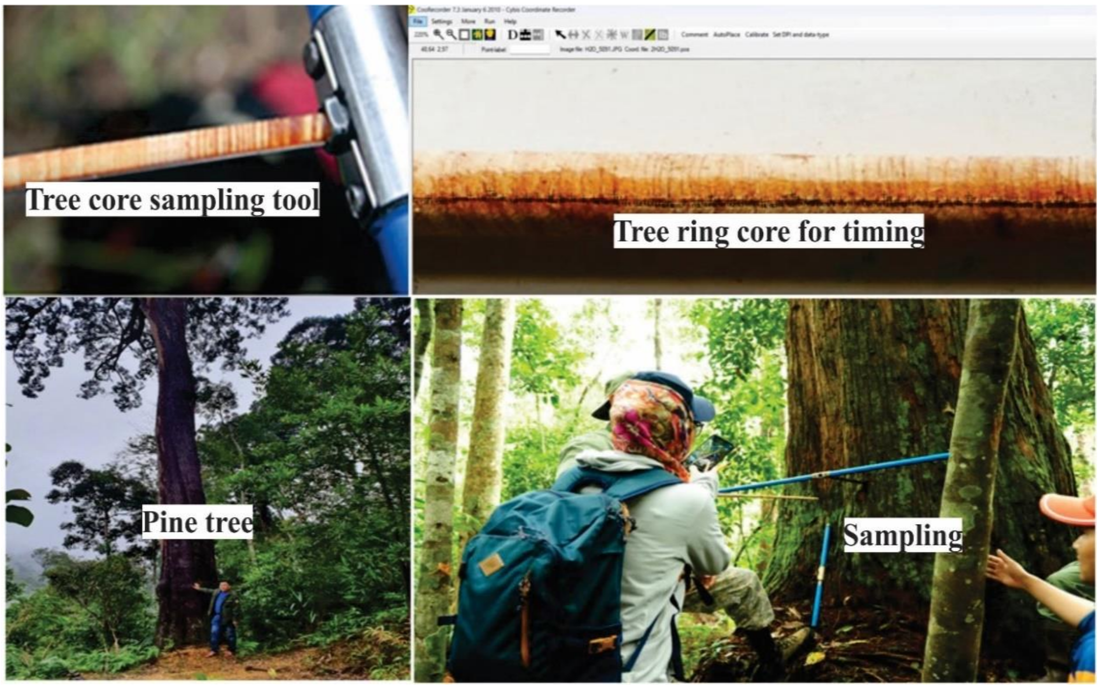

Figure 2. Tree ring sampling

2.5. Statistical analyses

Cluster analysis is used to divide the groups with similar characteristics. Similarity is the distance between clusters, compared to the most significant distance between any two individual variables (Chu Trung et al., 2024). Statistical analyses were performed by Minitab 18.

3. Results

3.1. Soil properties

Soil properties at three different depths are shown in Table 1. Soil texture analysis showed the predominance of fine sand (from 10.3−80.8%), limon (from 11.3−59.9%), and clay (from 10.1−47.5%), while the lowest content was found for coarse sand (from

0.02−4.16%). The accumulation of coarser particles, such as fine sand, coarse sand, and limon, was observed to increase with depth. At the same time, a decreasing trend was found for finer particles such as clay. Similar trends were observed for total nitrogen (ranging from 0.12% to 1.94%) and organic matter (ranging from 1.24% to 92.8%). Notably, soil pH was recorded at very low values, ranging from 1.8 to 3.84, with an increasing trend with depth.

Table 1. Data on soil properties and parameters ay the Nang pine forest in Quang Binh

Depth	Analysis parameter	Unit	E0	W0	S0	N0
0−20 cm	Coarse sand	%	0.03	0.45	1.85	2.61
	Fine sand	%	69.8	53.9	13.1	10.0
	Limon	%	11.3	24.3	37.5	59.9
	Clay	%	18.9	21.4	47.5	27.5
	pH		1.81	2	2.4	2.6
	Organic matter (OM)	%	92.1	92.7	21.9	22.0
	Total nitrogen (N)	%	1.77	1.94	0.55	0.6
20−50 cm	Coarse sand	%	0.02	0.36	1.89	1.47
	Fine sand	%	76.2	58.8	15.4	14.3
	Limon	%	12.6	27.1	41.3	41.9
	Clay	%	16.9	19.1	41.4	42.3
	pH		2.0	2.21	3.12	2.65
	Organic matter (OM)	%	13.0	13.1	7.5	3.09
	Total nitrogen (N)	%	0.61	0.67	0.25	0.19
50−100 cm	Coarse sand	%	0.05	0.71	2.9	4.16
	Fine sand	%	80.8	62.4	15.2	14.1
	Limon	%	17.0	36.7	56.6	58.8
	Clay	%	10.1	11.4	25.3	22.9
	pH		2.86	3.16	3.79	3.84
	Organic matter (OM)	%	4.88	4.92	1.16	1.24
	Total nitrogen (N)	%	0.48	0.53	0.15	0.12

Note: E-East, W-West, S-South, O-North

3.2. $\delta^{13}C$ of tree ring

The $\delta^{13}C$ values in tree rings are shown in Table 2, with each core cut at three levels: rings 0−20, 20−100, and 100−200 (ring represents dating, starting from 2023). Overall, the results show an increase in $\delta^{13}C$ in recent years, with values ranging from -22.44 ‰ to -24.08‰. Compared with other studies worldwide (Table 3), there are noticeable differences in $\delta^{13}C$ values across various regions. The negative mean $\delta^{13}C$ value in Vietnam is similar to that in Romania and Russia, countries with potential acid rain issues (Nagavciuc et al., 2018; Churakova et al. 2023). While those values are higher than other countries (Jonathan et al., 2019; Ha Lan Anh et al., 2023; Kostić et al., 2022; Torbenson et al., 2022; Kwak et al., 2016; Li et al., 2022).

Table 2. $\delta^{13}C$ results of tree rings for the average of 20 years, 100 years, and 200 years

$\delta^{13}C$	E0	W0	S0	N0	Average
20 years	-22.81	-22.44	-22.53	-22.72	-22.62
100 years	-23.67	-23.27	-23.37	-23.57	-23.47
200 years	-24.08	-23.68	-23.78	-23.98	-23.88

Table 3. $\delta^{13}C$ in tree rings in the world

Area	Mean	Min	Max	References
United State	-26.2	-28.1	-23.8	Jonathan et al., 2019
New Zeland	-27.2	-28.9	-26.0	Ha Lan Anh et al., 2023
Serbia	-25.8	-27.3	-23.9	Kostić et al., 2022
Germany	-25.3	-27.8	-23.5	Torbenson et al., 2022
Romania	-22.7	-25.1	-20.3	Nagavciuc et al., 2018
Korea	-26.3	-29.2	-25.7	Kwak et al., 2016
Russian	-21.9	-24.3	-20.8	Churakova et al., 2023
China	-26.77	-26.83	-24.33	Li et al., 2022
Vietnam	-23.47	-23.88	-22.62	This study

4. Discussions

The analysis of soil properties reveals a strong dependence of soil structure on depth. Previous studies indicate that soil formation is primarily a vertical process influenced by factors such as parent material, organisms, climate, topography, time, and space (McBratney et al., 2003). Consequently, most soil properties are closely related to depth (Kellman et al., 2015; Goebes et al., 2019). In particular, soil pH plays a crucial role in determining the chemical, biological, and physical properties of soil. It is regulated by interactions between soil components and their responses to natural processes, including mineral decomposition, organic matter breakdown, and acid rain (Russbelt et al., 2024). The low soil pH levels were found to influence biotic distribution, hinder organic matter decomposition, and reduce the nutrient absorption capacity (Zhao et al., 2011; Viet et al., 2013; Russbelt et al., 2024). The increase in pH at deeper layers may result from leaching and the accumulation of basic cations in lower soil horizons (Gurumurthy et al., 2009; Kumar et al., 2012; Getachew et al., 2012; Datta et al., 2015). Low soil pH creates an unfavorable environment for soil ecosystems, affecting the growth and survival of plant species in the region. A policy for land restoration, improvement, and protection in the study area is recommended.

Rainwater in natural tropical forests typically has a pH of 5.0 to 5.5 due to the presence of dissolved atmospheric CO_2. However, the soil cover in these forests often exhibits a much lower pH (≈2.0), indicating severe acidification, which is uncommon under natural conditions. This phenomenon may also be attributed to industrial activities that lead to acid rain. Additionally, frequent flooding in tropical forests, caused by prolonged rainfall, results in the accumulation of large amounts of partially decomposed organic matter. The subsequent decomposition of this organic matter generates organic acids, which further lower the soil pH. Moreover, soil contamination with acidic compounds such as sulfuric acid (H_2SO_4) and nitric acid (HNO_3), or acidic water sources from streams and lakes, exacerbates soil acidification. Vietnam, particularly its central region, is one of the most vulnerable countries in Asia to acid rain (Pham et al. 2020). This region experiences frequent extreme weather events, including storms and floods, which significantly impact soil properties. Precipitation and temperature data from the past 65 years (Fig. 4) indicate a pattern of high precipitation accompanied by a declining temperature trend in the study area over recent years. These two climatic factors are closely linked to variations in soil pH, particularly within forest ecosystems, where microclimatic conditions vary according to topographic orientation and vegetation cover. Precipitation plays a decisive role in driving soil acidification dynamics. High precipitation intensifies the leaching of base cations, such as calcium, magnesium, and potassium, from the soil matrix, consequently lowering soil pH (Zhao et al., 2018b; Zhou et al., 2019; Chatterjee et al., 2024; Russbelt et al., 2024).

Meanwhile, numerous studies have also reported the influence of temperature on soil pH (Liu et al., 2013; Yan et al., 2019). Warmer temperatures typically accelerate the decomposition of organic matter, resulting in the release of organic acids that contribute to soil acidification (Galluzzi et al., 2024). Conversely, in cooler climatic conditions, the slower rate of organic matter decomposition allows for its gradual accumulation, which over time can also generate organic acids, further contributing to soil acidification (Brady and Weil, 2008). The observed high rainfall, combined with decreasing temperatures in recent years, may have simultaneously enhanced the leaching of base cations and the accumulation of organic acids, creating a synergistic effect that accelerates soil acidification within this tropical forest ecosystem. This finding highlights the significant role of long-term climate variability in shaping soil chemical properties, underscoring the vulnerability of these soils to ongoing environmental change.

In this study, the soil pH increased with depth and was inversely related to the decrease in total organic matter. Therefore, it is possible that soil acidification in this area could be related to acid rain and organic matter content in the study soil. It can be observed that there are differences in soil properties across the different sampling locations. Overall, the data show that the locations can be divided into two groups with similar soil properties: East-West and South-North (Fig. 3). This suggests that topography and climate are key drivers of soil property variation, with acid rain playing a significant role in the soil acidification process. The depth-dependent decline in total nitrogen further supports the hypothesis that nitrogen deposition from industrialization accelerates soil acidification (Ito et al., 2011; Šantrůčková et al., 2007; Chen et al., 2010).

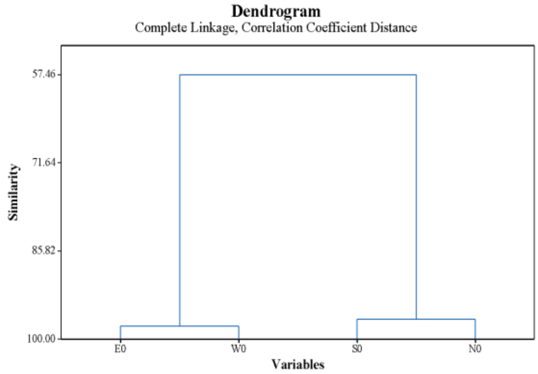

Figure 3. Similarity of soil properties between sampling locations

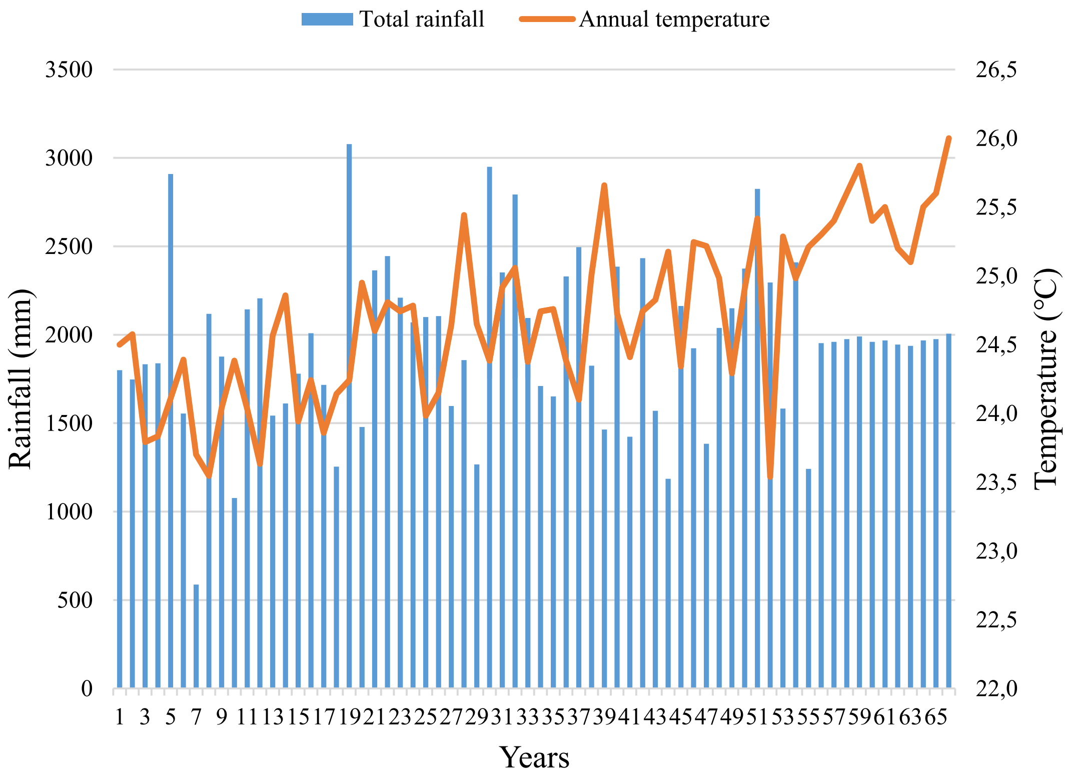

Figure 4. Total rainfall and annual temperature 65 years ago

Table 4 shows a negative correlation between soil pH and δ¹³C values. This result is consistent with previous studies on the direct impact of soil acidification on plant ¹³C isotopes (Savard, 2010; Viet et al., 2013). This reflects the increasingly pronounced process of soil acidification in Phong Nha-Ke Bang National Park. The vegetated soil layer has an extremely low pH (≈ 2.0), and recent years have seen low δ¹³C values (-22‰), suggesting the presence of multiple potential causes in this forest. This may create a challenging environment for soil ecosystems, affecting the growth and development of species in the area. Soil pH can change over relatively short periods (a few years to a few decades) due to biological processes, vegetation, and soil management activities (Norfleet et al., 2003; Goebes et al., 2019). Therefore, measures to improve soil pH are necessary, such as adding vegetation and planting suitable trees to reduce acidity. Utilizing bare land to plant short-term crops, such as vegetables or shade-tolerant fruit trees, combined with appropriate fertilization, can help raise the pH of the topsoil. This will promote the development of pine tree roots, enhancing nutrient absorption, supporting healthier growth, and extending the lifespan of the trees. Based on the preliminary findings, future research should focus on long-term monitoring of soil pH and δ¹³C in tree rings to clarify the response of forest ecosystems to soil acidification under changing climatic conditions. Expanding the spatial and species scope, combined with experimental validation and the integration of isotope data into environmental monitoring frameworks, will contribute to a deeper understanding of the mechanisms driving acidification and their implications for sustainable forest management and climate change adaptation.

Table 4. Relationship between soil pH and $\delta^{13}C$

	δ¹³C_E0	***δ¹³C_W0***	***δ¹³C_S0***	***δ¹³C_N0***	***pH_E0***	***pH_W0***	***pH_S0***	***pH_N0***
δ¹³C_E0	1.00							
δ¹³C_W0	1.00	1.00						
δ¹³C_S0	1.00	1.00	1.00					
δ¹³C_N0	1.00	1.00	1.00	1.00				
pH_E0	-0.85	-0.85	-0.85	-0.85	1.00			
pH_W0	-0.85	-0.85	-0.85	-0.85	1.00	1.00		
pH_S0	-0.98	-0.99	-0.98	-0.98	0.93	0.93	1.00	
pH_N0	-0.77	-0.78	-0.78	-0.77	0.99	0.99	0.87	1.00

5. Conclusions

This study applied and evaluated an innovative approach that combined soil pH analysis with tree-ring δ¹³C measurements to assess forest soil acidification in the Nang pine forest of Phong Nha-Ke Bang National Park. This integrated approach provides both current soil condition assessments and historical environmental reconstructions, addressing key limitations of traditional soil acidification research methods. From the results obtained, several important conclusions were drawn:

Soil texture analysis revealed that fine sand was predominant, while coarse sand had the lowest content. There is a difference in the distribution of soil components with depth, with an increasing trend for fine sand, coarse sand, and limon. In contrast, the finer particles, such as clay, total nitrogen, and organic matter, exhibit a decreasing trend in their recorded values. The combination of elevated rainfall levels and a trend of declining temperatures in recent years appears to have promoted both the leaching of base cations and the build-up of organic acids. Soil pH values were very low and increased with depth, possibly due to leaching and the accumulation of basic cations in deeper soil layers, which was related to total nitrogen and organic matter. This suggests that the soil is experiencing severe acidification, which could be caused by both natural factors and industry activities (e.g., acid rain). Additionally, differences in soil properties were noted between sampling sites, with the East-West and South-North regions exhibiting similar soil characteristics. This suggests that topography and climate may play a significant role in the variation of soil properties and acidification in this region.

A negative correlation was established between soil pH and $\delta^{13}C$. The results of $\delta^{13}C$ analysis in tree growth rings showed a trend of increasing $\delta^{13}C$ values in recent years, ranging from -22.44‰ to -24.08‰. This trend mirrors the changes in soil pH, reflecting the growing acidification in Phong Nha-Ke Bang National Park. This suggests that tree-ring isotopic signatures can serve as sensitive bioindicators of long-term soil chemical changes, demonstrating the feasibility of $\delta^{13}C$ measurements as a retrospective tool for monitoring soil acidification over time scales an essential advantage over conventional methods that primarily capture instantaneous conditions.

This initial study integrates tree-ring $\delta^{13}C$ measurements with soil property analysis to elucidate acidification processes in tropical forest ecosystems. Although preliminary and requiring further detailed study, the results demonstrate the potential of this approach to overcome the limitations of traditional methods, which capture only instantaneous or short-term conditions. The integration of $\delta^{13}C$ isotope analysis with soil property data offers a promising methodological pathway for investigating soil degradation processes, such as acidification. These findings enhance our understanding of the mechanisms driving forest soil acidification and support the development of sustainable management strategies and climate adaptation measures in Vietnam, a country heavily affected by climate change.

Acknowledgements

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