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Review

Soil savvy: how stable isotopes are shaping forest ecosystem management

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Abstract

This literature review synthesizes recent research on use of stable isotopes to advance forest ecosystem management. Stable isotopes provide insights into soil fertility, nutrient cycling, climate variability, and pollution impacts by tracing carbon, nitrogen, and water dynamics. Microbial activity influences on soil conditions are also highlighted. Integration of soil metrics with genomic and forest management strategies allows for an understanding of carbon sequestration and soil health while supporting adaptive approaches to climate change. Seasonal variations in nitrogen uptake and the role of $\delta^{15}N$ in nitrogen cycling illustrate the complex interactions between biotic and abiotic factors in temperate and tropical forests. Isotopic tracing reveals how urbanization and pollution disrupt nutrient cycles and inform urban forest conservation efforts through contamination source identification and assessment of heavy metal bioavailability. Recent advancements in isotopic techniques, including multi-isotope systems, enable precise measurements and refine ecosystem-level predictions to guide long-term forest management and restoration efforts. These developments are particularly valuable for assessing impacts of climate, pollution, and anthropogenics on soil health. This review also identifies future research directions, including long-term carbon stability, effects of management practices on isotopic signatures, and microclimatic influences to improve soil conservation and ecosystem sustainability in the context of sustainable land management.

Key words: biogeochemical processes, carbon sequestration, contamination tracing, ecological restoration, environmental monitoring

Introduction

Soil is often regarded as the foundation for terrestrial ecosystems and is essential in determining plant growth outcomes, nutrient cycling, and overall ecosystem health. Existing approaches in this area rely primarily on indirect measures, which highlights the need for more precise methods. Understanding soil processes and dynamics is imperative for implementing sustainable land management practices. In forests and plantations, soil health has a direct impact on ecosystem productivity and resilience. Stable isotopes, such as carbon-13 (^{13}C) and nitrogen-15 (^{15}N), have emerged as invaluable tools in soil science. These isotopes function as both tracers and integrative signatures and reveal how environmental changes affect biogeochemical processes. $\delta^{13}C$ is often used as a physiological signature for carbon assimilation and its enrichment reflects decreased stomatal conductance during drought conditions. Determination of whether nitrogen originates from symbiotic fixation, organic matter, or anthropogenic deposition can be investigated by using $\delta^{15}N$ as a tracer. These isotopes offer key insights into forest soil productivity by tracing carbon, nitrogen, and water dynamics across ecosystems, thereby uncovering nuanced relationships between soils, plants, and the atmosphere. However, gaps remain in how isotopic data are applied across varied soil types. Recent literature has highlighted the expanding applications of stable isotopes in soil science (Table 1). Several recent works explore novel methodologies for isotopic analysis to enhance our understanding of soil processes and dynamics (Guidi et al. 2023; Jeon et al. 2024). Kang (2021) highlighted that microbes are key drivers of climate-related biogeochemical processes and emphasizes their importance in soil studies. Consequently, stable isotopes are indispensable tools for comprehensively evaluating soil productivity, suitability, and health within forested environments and plantations worldwide (Supplemental Files S1 and S2).

The stable isotope approach is based on the measurement of particular isotopes (^{13}C, ^{15}N, or ^{2}H) that vary in their neutron count and are classified as “heavy” or “light” based on their neutron richness or scarcity, respectively (Bahn et al. 2012). The concentrations of stable isotopes in a sample are represented as the molar ratio of heavy to light isotopes. The ratios of heavy to light isotopes may provide insights into

Table 1. Types of stable isotopes and their applications in soil research.

Isotope	Symbol	Abundance in nature	Application in soil and ecosystem studies	Key insights/benefits	References
Carbon	$\delta^{13}C$	1.1% of carbon in nature	Tracing carbon sources, soil organic carbon (SOC) dynamics, and plant–carbon interactions	Helps trace carbon flow between plants, soil, and microbes. Provides insights into carbon sequestration potential and soil health. Precipitation and ecosystem influences.	Canadell et al. 2007; McCorkle et al. 2016; Kuzyakov et al. 2000; Rijk and Ekblad 2020; Zwetsloot et al. 2020; Dulamsuren and Hauck 2021; Craig et al. 2022; Diao and Wu 2024; Piñeiro et al. 2024
Nitrogen	$\delta^{15}N$	0.37% of nitrogen in nature	Studying nitrogen cycling, nitrogen fixation by plants, and soil nitrogen transformations	Used to trace nitrogen sources, cycling rates, and nutrient dynamics in soils. Helps understand fertilizer application and ecosystem nitrogen balances.	Kuzyakov et al. 2000; Canadell et al. 2007; Gerhart and McLauchlan 2014; McCorkle et al. 2016; Lyu et al. 2019; Dulamsuren and Hauck 2021; Henriksson et al. 2021; Ma et al. 2021; Mao et al. 2024; Piñeiro et al. 2024
Oxygen	$\delta^{16}O$	0.2% of oxygen in nature	Water cycle studies, soil water content, and plant water uptake	Traces water movement through soils and plants. Useful for assessing soil moisture levels and evaporation rates.	Canadell et al. 2007; McCorkle et al. 2016; Kleine et al. 2020; Pistocci et al. 2020; Wang et al. 2020*a*; Badea et al. 2021; Cherubini et al. 2021; Gallarotti et al. 2021; Mas et al. 2024
Sulfur	$\delta^{32}S$	4.2% of sulfur in nature	Sulfur cycling in soil, plants sulfur uptake, and microbial sulfur transformations	Helps in understanding sulfur dynamics in soils, nutrient cycling, and soil microbial activity.	Schroth and Sinclair 2003; Canadell et al. 2007; Marschner and Rengel 2007; Carter and Gregorich 2008; McCorkle et al. 2016; Chang and Sun 2017; Cheng and Chang 2020
Hydrogen	$\delta^{2}H$	0.015% of hydrogen in nature	Tracing water sources, plant transpiration, and soil water movement	Used in studying the movement of water through ecosystems and the uptake of soil water by plants.	Schroth and Sinclair 2003; Canadell et al. 2007; Marschner and Rengel 2007; Carter and Gregorich 2008; McCorkle et al. 2016; Chang and Sun 2017; Cheng and Chang 2020; Kleine et al. 2020; Henriksson et al. 2021; Liu et al. 2021; Mas et al. 2024
Phosphorus*	^{32}P	Radioactive in nature, but stable isotopes used in studies	Investigating phosphorus cycling in soil and plant uptake	Provides insights into phosphorus availability and its relationship with microbial activity and soil properties.	Schroth and Sinclair 2003; Canadell et al. 2007; Marschner and Rengel 2007; Carter and Gregorich 2008; McCorkle et al. 2016; Chang and Sun 2017; Cheng and Chang 2020

*^{32}P is a radioactive isotope of phosphorus commonly used as a tracer in research. It is not stable, and the only stable isotope of phosphorus is ^{31}P.

several environmental and physiological processes. A positive δX value indicates that the sample has a higher concentration of the heavy isotope compared to the standard, while a negative δX value signifies a lower concentration of the heavy isotope relative to the standard. In plants, for example, δ^{13}C in tissues mostly indicates the equilibrium between CO_2 influx into a leaf, regulated by stomatal conductance, and the CO_2 needed by photosynthetic enzymes (Ehleringer et al. 1989). In this example, δ^{13}C can act as a signature for water-use efficiency as reduced stomatal opening is indicative of drought conditions. Conversely, δ^{15}N may be seen as both an integrator of the N cycle and an indicator of plant stress responses (Robinson 2001). Enrichment in δ^{15}N can also reflect nitrogen losses via denitrification or ammonia volatilization while depletion suggests uptake from symbiotic fixation or low-input systems. δ^{15}N can act as a tracer and serve as an effective method for identifying the nitrogen source in plants capable of symbiosis, such as those associated with rhizobia or mycorrhizas (Mao et al. 2024). Consequently, δ^{15}N commonly used as a source identified and a tracer for N cycling efficiency. Isotopes of oxygen (δ^{18}O) and hydrogen (δ^{2}H) can be used to ascertain water cycle dynamics as they often act as tracers of water source pathways. Their values are determined by comparing isotopic compositions of plant xylem water with known soil or precipitation sources. This enables researchers to infer seasonal and depth-specific water uptake from all probable source fluids (Ehleringer and Dawson 1992).

The use of stable isotopes is globally acknowledged, with several studies that are ecosystem-scale (Shestakova et al. 2019; Charbonnier et al. 2020) and even on a global scale (Ballantyne et al. 2011; Gerhart and McLauchlan 2014; Cornwell et al. 2018). For example, Ballantyne et al. (2011) studied a global analysis of the seasonal variations of the sources of CO_2 into the atmosphere. In another study, almost 4000 plant species–site combinations distributed across the five continents were used to evaluate climatic and soil drivers of δ^{13}C on leaves (Cornwell et al. 2018). Here, δ^{13}C values functioned as integrative climate signatures, where lower values often designated greater stomatal openness in wet or shaded environments. There are also stable isotope studies about the fluxes of δ^{13}C and δ^{15}N in tropical (Gallarotti et al. 2021; Paul et al. 2021; Liu et al. 2022; Benavides-Tocarruncho et al. 2024; Raihan 2024), temperate (Porras et al. 2017; Pistocci et al. 2020; Bai et al. 2021; Ma et al. 2021; Diao and Wu 2024), and boreal (Graydon et al. 2009; Marty et al. 2017; Dulamsuren and Hauck 2021; Henriksson et al. 2021; Manninen et al. 2022) forest types. Comparisons among these climates were reported in several studies. Martinelli et al. (1999) found 6.5% and 8% more foliar and soil δ^{15}N, respectively, in tropical forests than in temperate forests. This particular enrichment is interpreted as an indicator of increased nitrogen loss through denitrification and leeching in warm, wet climates. Marty et al. (2017) showed forest N deposition is driven by precipitation and temperature in boreal and temperate forests leading to modification of δ^{15}N values in soils and plants. These examples illustrate how δ^{15}N can be used as a tracer for both anthropogenic and climate nitrogen deposition. Challenges exist in accurately interpreting isotopic signatures across diverse forest ecosystems, particularly concerning long-term soil health and management in a changing climate. Their use is essential for understanding the impacts of environmental factors such as climate change, extreme weather events, and new land management practices on soil fertility.

Effective monitoring of forest plants and soil may improve soil production, suitability, and health in forested areas and plantations; hence, stable isotopes can provide several insights. The purpose of this review is to highlight the significance of isotopic research in forest science, as well as the primary conclusions that have been obtained from these studies, and to discuss how these studies may be applied to soil health, soil nutrient cycling, water availability, and soil pollution. This review provides a summary of the most recent studies on their application to forest soils, including topics such as nutrient cycle, carbon sequestration, microbial interactions, and pollution tracking. In addition, we highlight developing technologies in the field of isotopic analysis, analyze knowledge gaps, and suggest future research goals with the goal of improving soil conservation and sustainable land management techniques.

Methodology

This literature review employed a systematic approach to identify and synthesize studies examining the role of stable isotopes in forest ecosystem management. Exhaustive searches were conducted in Google Scholar, Web of Science, and the Purdue Library system, using keywords derived from the manuscript title and expanded to encompass broader concepts such as nutrient cycling, pollution assessment, microbial activity, and soil isotopic techniques. Peer-reviewed journal articles, books, and dissertations published from 2000 onward were considered with older works studied for background information. Selection criteria focused on rigor and relevance to stable isotope applications in both temperate and tropical forest ecosystems. Efforts were taken to identify works that also included advances in compound-specific and multi-isotope approaches. Titles and abstracts were screened, and the texts were reviewed to ensure they aligned with the review objectives. The literature cited sections from the most recent work were examined to identify additional sources relevant to the work. A synopsis of each work was extracted and organized beneath the section headings chosen for this review, including carbon and nitrogen tracing, microbial influences on soil conditions, and pollution impacts on microbial communities. Books and dissertations were considered if they provided the background necessary to ensure a comprehensive and balanced synthesis of work.

Stable isotopes and forest soils

Dawson and Siegwolf (2007) reported nearly two decades ago that using stable isotopes in materials such as carbonates, feathers, and tree-ring cellulose has provided invaluable insights into carbon storage, ecosystem functioning, and soil health. Their research laid the groundwork for modern applications of isotopic data in tracking ecological changes and understanding soil productivity and enhances long-term

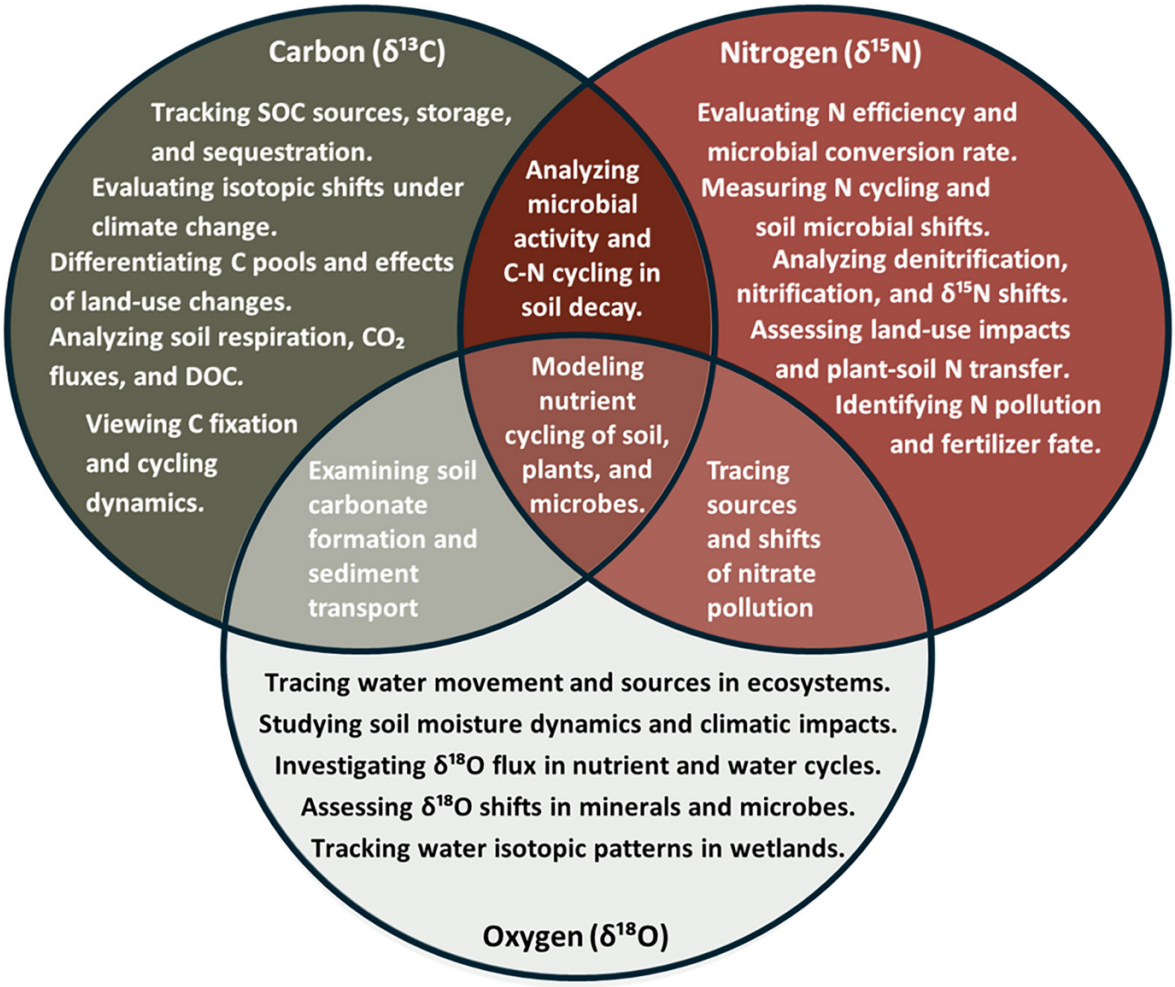
environmental monitoring. A chief application of stable isotopes in soil productivity studies is using $\delta^{13}C$ and $\delta^{18}O$ as signatures to trace carbon and water relations across plant ecosystems. Werner et al. (2012) reported on the progress-based understanding, technological developments, and challenges with using carbon, hydrogen, and oxygen stable isotopes to investigate plant carbon and water relations across different scales. Their work highlighted how isotopic signatures improve our understanding of carbon assimilation processes and the influence of soil moisture on plant productivity. Similar to $\delta^{13}C$ that is enriched with a reduction in stomatal conductance in dry soils, $\delta^{18}O$ enrichment can trace evaporative demand as the heavier isotopes accumulate with increased transpiration. Isotopic data provide insights into how plants allocate carbon to roots and SOM. Shifts in belowground carbon under nutrient-limited or water-limited conditions can be reflected in isotopic enrichment in roots or soil and show $\delta^{13}C$ can function as a tracer of carbon allocation. This is crucial for assessing soil carbon storage and is a key determinant of soil productivity. The study underscored the strengths and limitations of stable isotope methods to help quantify soil fertility in various forest ecosystems by linking isotopic data with vegetation growth patterns due to environmental and physiological complexities. Similarly, Diao and Wu (2024) explored how extreme precipitation events influence the $\delta^{13}C$ isotopic signatures of ecosystem respiration in a temperate forest. Their findings revealed that extreme weather events, such as heavy rainfall, can dilute carbon isotope signals from photosynthesis that are robust under normal conditions and hinder the ability to track soil carbon fluxes accurately. Here, $\delta^{13}C$ acts as a tracer of soil respiration sources. Heavy rainfall increases microbial activity and causes mixing with older soil carbon. This muddling of sources hides the isotopic signal of new photosynthate and produces a less distinct and often depleted $\delta^{13}C$ signal in respired CO_2. This research provides new insights into the dynamic relationship between climate variability and resultant soil productivity and shows that stable isotopes can provide much-needed insight into the stability of soil productivity in the face of fluctuating weather patterns.

Stable isotopes also provide valuable insights into the roles of carbon, water, and nitrogen dynamics in maintaining soil fertility and plant productivity. Amundson et al. (2003) used $\delta^{15}N$, mean annual precipitation, and mean annual temperature (MAT) to explore global patterns of soil and plant isotopic composition and revealed how nitrogen cycling influenced soil productivity. In this example $\delta^{15}N$ was used as a source/sink indicator to infer nitrogen retention and loss pathways. Lower $\delta^{15}N$ values were found in environments where nitrogen was tightly conserved by processes like plant uptake and microbial immobilization. In contrast, higher $\delta^{15}N$ values indicated ecosystems with rapid nitrogen turnover and greater losses through leaching or gaseous emissions such as denitrification. Their results indicated that lower temperatures and greater precipitation rates more efficiently conserved and recycled mineral nitrogen. They also provided critical insights into nutrient cycling and soil health by identifying distinct nitrogen sources and pathways within soils. In this isotopic approach $\delta^{15}N$ acts as both a tracer of nitrogen sources and a marker of nitrogen-use efficiency under different climate conditions by tracking nutrient movement and highlighting areas at risk of nutrient loss.

Isotopic techniques are not limited to nutrient and carbon cycling and offer a means to investigate historical soil productivity (Fig. 1). Tree-ring analysis is another application of stable isotopes that has proven to be effective for studying soil productivity over long timescales. Most studies focus on the tree ring components cellulose and isotope proxies like $\delta^{13}C$ and $\delta^{18}O$ because of their distinct isotopic ratios (Cherubini et al. 2021). The $\delta^{13}C$ in cellulose reflects long-term climate conditions by capturing stomatal regulation and carbon uptake during tree ring formation and $\delta^{18}O$ records changes in evaporative demand and the isotopic composition of rainfall. The isotopic signature of cellulose is generally noted to be the most accurate indicator of environmental conditions during tree growth because it remains chemically stable and is unaltered by secondary processes. Badea et al. (2021) presented a comprehensive study describing the recent advances in $\delta^{13}C$ and $\delta^{18}O$ analysis of the photosynthetic and evaporative processes by which cellulose is extracted from tree rings, emphasizing the potential for dendrochronology to reveal historical variations in soil moisture conditions, nutrient availability, and forest productivity. They used $\delta^{13}C$ to estimate intrinsic water-use efficiency (iWUE) and showed that $\delta^{18}O$ enrichment under strong evaporative demand makes both isotopes reliable indicators of soil moisture conditions and their effects on forest productivity. The study of tree growth about isotopic fractionation offers further insights into soil productivity under changing environmental conditions. Shestakova et al. (2019) investigated spatio-temporal tree growth patterns and ring widths across Europe and linked $\delta^{13}C$ fractionation with variable climate scenarios. Here, $\delta^{13}C$ indicated differences in soil water availability across regions with greater enrichment showing drought-prone soils and depletion signaling mesic or well-watered conditions. Their research illustrated how stable isotopes can help differentiate between local soil productivity levels by tracing how trees respond to variations in soil moisture and nutrient availability. Coupling this approach with leaf gas exchange measurements helps identify areas where soil productivity may be rapidly declining in response to environmental stresses while simultaneously supporting better land management and conservation efforts.

These findings underscore the broad applicability of stable isotopes in addressing localized and global challenges to soil productivity. Overall, stable isotope analysis plays a leading role in assessing soil productivity by providing insights into carbon and nitrogen cycles, water relations, and the impacts of extreme weather events and climate change. By functioning as source indicators (e.g., of nitrogen inputs), process signatures (e.g., of water-use efficiency), and tracers (e.g., of carbon allocation), isotopes help untangle the mechanistic drivers of soil health. Current isotope evaluation methods offer both temporal and spatial perspectives on soil fertility and enable more accurate assessments of soil health and productivity. Greater integration of stable isotopes into soil productivity studies not only

Fig. 1. Venn diagram comparing different isotopic techniques (e.g., carbon, nitrogen, and oxygen isotopes) and their overlapping roles in soil science.



enhances our knowledge of plant–soil interactions but also paves the way for valuable discoveries in adaptive forest management strategies in the face of environmental challenges (Table A1).

Soil health and suitability assessment

Forest soils play critical roles in supporting ecosystem services such as water purification, habitat provision, and timber production (von Wilpert 2022). Environmental changes and variations in forest management practices dramatically threaten essential functions like soil nutrient transport and water infiltration. Assessing soil health involves considering soil suitability and the likelihood that the soil will support diverse plant and microbial communities under varying environmental conditions. Soil health and suitability are continuous influencers of ecosystem stability, forest productivity, and fortitude in response to environmental changes. Recent studies using stable isotopes and other innovative techniques have bolstered our assessments of soil health and have provided valuable insights into nutrient cycling, water movement, and the effects of soil stewardship practices.

A fundamental aspect of soil suitability is grasping how different tree species interact with critical soil nutrients such as nitrogen (N). Henriksson et al. (2021) explored how tree water uptake enhances N acquisition in boreal forests under different ambient levels of N using $\delta^{15}N$ as a tracer of nitrogen source and cycling efficiency and $\delta^{2}H$ as a tracer of plant water source. They found that water uptake significantly improved N acquisition in fertilized soils, but the effect was diminished in N-poor conditions. $\delta^{15}N$ values indicated increased nitrogen assimilation under fertilized conditions through enrichment, while $\delta^{2}H$ values confirmed the uptake of shallower soil water during active plant growth. These isotopic shifts demonstrate how water movement and N uptake are interconnected by highlighting the importance of water availability considerations when assessing soil nutrient dynamics and suitability for different tree species. Water availability shapes soil nutrient dynamics, and microbial activities also play a crucial role in maintaining soil health. These observations are particularly important in the face of anthropogenic pressures. Bhaduri et al. (2022) report a consensus regarding soil degradation and ecosystem restoration. They emphasize the vital need to incorporate the

benefits and impact of microbial activities in soil health and how anthropogenic activities such as mining and pollutants influence soil systems.

Another dimension of soil health is its ability to support tree growth under varying environmental conditions. Wang et al. (2020*c*) explored trends identified between tree-ring δ^{15}N and δ^{18}O alongside iWUE and streamflow with the growth of riparian trees. Their results showed that nitrogen availability was a more significant factor in regulating tree growth than streamflow. δ^{15}N indicated nitrogen sources and sinks as enriched values showed greater losses or inputs. Depleted values indicated conservative cycling or fixation while δ^{18}O linked water stress to tree growth. This indicated that riparian soils with adequate nitrogen levels are more suitable for tree growth. N availability is aligned with water accessibility and is a critical determinant of soil health in riparian zones. These studies also highlight the importance of understanding carbon cycling and organic matter stabilization in soils.

Water–soil–vegetation dynamics offer valuable insights into ecosystem resilience in addition to playing major roles in N cycling. Kleine et al. (2020) explored water–soil–vegetation dynamics with forest and grassland soils using δ^{2}H and δ^{18}O as tracers of water movement. Differences in water retention, soil moisture storage, and the impact on ecohydrological partitioning between the sites were noted. Their analysis concluded that forest soils were drier than grasslands because of high transpiration and interception rates. Enriched δ^{18}O and δ^{2}H in plant xylem water traced shallow versus deep water uptake and indicated ecohydrological stress from evaporative loss. They suggested stable isotopes were essential because they could track evapotranspiration, groundwater recharge, and plant water uptake if spatial-temporal variations in soil water storage and management are to be adequately addressed under climate change scenarios. The effects of stressors such as N deposition are further confounded when combined with anthropogenic factors like drought stress. Dulamsuren and Hauck (2021) analyzed larch (*Larix occidentalis* Nutt.) tree needles with δ^{13}C as a signature of water-use efficiency and δ^{15}N as a N source indicator and noted that drought stress was significant. However, δ^{15}N values indicated nitrogen availability was more crucial in tree growth. Here, δ^{13}C enrichment during drought signaled reduced stomatal conductance and higher water-use efficiency, while enriched δ^{15}N indicated nitrogen from livestock sources. Their study suggested that N supplementation might boost forest resilience during drought periods by enhancing carbon gain.

Stable isotopes have also been used to assess the processes that stabilize organic matter in soils to provide insights into soil carbon cycling. Angst et al. (2019) investigated the stabilization mechanisms of soil organic matter (SOM) by highlighting how plant traits, soil texture, species identity, and organic material inputs, affect SOM stabilization. They used δ^{14}C to trace the age of organic matter and δ^{15}N to identify nitrogen retention and microbial activity. Depleted δ^{14}C indicated older stabilized carbon pools while shifts in δ^{15}N showed microbial processing and nitrogen retention in fine-textured soils. Angst et al. (2019) suggested that focusing on smaller, more sensitive SOM pools (e.g., particulate organic matter) would clarify species-level impacts on soil health, especially as climate influences microbial processing rates.

Long-term soil health is increasingly important in the context of climate-induced ecosystem change. Fotelli (2021) demonstrated climate change-induced species shifts in Mediterranean ecosystems, where the drought-tolerant shrub *Phyllirea latifolia* displaced *Quercus ilex* over 21 years due to decreasing soil water availability. While not an isotopic study per se, this example underscores how long-term ecohydrological patterns that are detectable with δ^{18}O or δ^{2}H could have confirmed such water-limitation dynamics. The author stressed the importance of proactive strategies like assisted migration to support resilience.

Microbial communities in forest soils are the initial and consistent drivers of nutrient cycling and remain the foundation of healthy soils. They are vital for maintaining forest soil fertility during anthropogenic changes and especially when under environmental stressors like nitrogen deposition. Piñeiro et al. (2024) examined how chronic N deposition affects soil microbial traits associated with different mycorrhizal types. Stable isotope studies utilizing δ^{13}C and δ^{15}N showed that excess N could increase soil carbon storage and decrease microbial respiration and biomass. δ^{13}C enrichment in SOM pointed to greater microbial carbon retention, marking it as a source signature, while enriched δ^{15}N in arbuscular mycorrhizal (AM) microbes signaled shifts in nitrogen processing under chronic nitrogen deposition. Ectomycorrhiza (ECM) species did not exhibit the same pattern. This is an especially critical consideration in ecosystems subjected to long-term nitrogen deposition. Gaining a greater comprehension of how different mycorrhizal relationships influence soil microbial communities is key for determining the adequacy of soil for supporting diverse plant species. The role of soil microbial traits and nitrogen deposition complicates soil health assessments further and highlights the need for tailored approaches to these environmental concerns (Table 2).

Soil suitability in oak–pine and shrub-containing Mediterranean forests is influenced by both water availability and species diversity. Mas et al. (2024) examined soil suitability in Mediterranean oak–pine forests by analyzing δ^{2}H and δ^{18}O to assess species-driven water partitioning during drought. They found that even higher species diversity did not significantly reduce drought impacts. δ^{18}O enrichment in xylem water suggested shallow water uptake and high evaporative demand across species. This highlights the need for continued innovation in soil management strategies and the importance of multidimensional approaches to soil health that incorporate both environmental and biological factors. The ability to maintain current ecosystem services while continuing to evaluate additional options highlights the importance of predictive models and active soil management strategies.

There are complex interactions within ecosystems affecting soil productivity and stability that integrate genetic and ecological data with stable isotope findings to provide a comprehensive approach to assessing and improving soil health. Integrating genomic and productivity traits into forest

Table 2. The various carbon assimilation pathways used by microbes.

Pathway	Definition	Representative microbes	Environmental relevance	References
Autotrophy	Inorganic carbon (CO_2) fixed into organic molecules	Cyanobacteria, nitrosomonas, thiobacillus	Essential in primary production and carbon cycling in oceans, soils, and wetlands.	Berg et al. 2010; Tang et al. 2020; Allan et al. 2021; Pace et al. 2021; Wang et al. 2021*b*; Zhang et al. 2021*b*
Photoautotrophy	Light energy drives carbon fixation.	Cyanobacteria, purple sulfur bacteria	Primary producers in aquatic and terrestrial ecosystems; generate oxygen and organic carbon.	Nguyen et al. 2021; Řeháková et al. 2022; Liao et al. 2023; Liu et al. 2023
Chemoautotrophy	Chemical energy (inorganic compound oxidation) drives carbon fixation.	Nitrosomonas, nitrobacter, thiobacillus	Critical in nutrient cycling, particularly nitrogen and sulfur in soils and aquatic systems.	Liao et al. 2020; Braun et al. 2021; Zheng et al. 2025; Shi et al. 2023; Wang et al. 2023*b*
Heterotrophy	Organic carbon assimilated from the environment	*Escherichia coli*, bacillus, fungi	Decompose organic matter, recycling carbon and nutrients.	Gao et al. 2022; Hermans et al. 2022; Manninen et al. 2022; Szlachcic and Rożen 2023; Zhang et al. 2024
Photoheterotrophy	Light energy supplements organic carbon assimilation.	Purple nonsulfur bacteria	Important in nutrient-poor aquatic environments where light but little organic carbon is available.	Hamard et al. 2021; Kovacs and Kovacs 2023; Smenderovac et al. 2023; Fu et al. 2024
Chemoheterotrophy	Organic molecules used for carbon and energy sources.	*E. coli*, fungi, lactobacillus	Dominant carbon assimilation strategy in most ecosystems, breaking down organic matter.	Shiau and Chiu 2020; Kang 2021; Wang et al. 2023*b*; Niu et al. 2024
Mixotrophy	Uses inorganic (CO_2) and organic carbon sources in varied habitats and conditions.	Paramecium, pseudomonas	Adaptable to fluctuating environments, often found in aquatic and soil ecosystems.	Onipchenko et al. 2021; Yagame et al. 2021; Firmin et al. 2022; Zhou et al. 2022; Wang et al. 2023*b*

management practices is also essential for enhancing soil suitability. Cappa et al. (2022) focused on white spruce (*Picea glauca* (Moench) Voss) and recommended integrating $\delta^{13}C$ status into forest breeding programs to combine genomic data with productivity and climate-adaptability traits. Higher $\delta^{13}C$ values indicated greater water-use efficiency, suggesting improved adaptation to dry or nutrient-poor soils and making this trait valuable for selecting resilient species. An additional benefit of this handpicking is its positive contribution to carbon sequestration and soil nutrient cycling. This approach highlights the potential for integrating genetic information into soil suitability assessments and offers a more holistic view of soil health that accounts for both biological and environmental factors.

Soil suitability and health assessments benefit from a multidimensional approach that incorporates microbial community dynamics, nutrient cycling, species-specific traits, and stable isotope analysis. Stable isotopes serve as diagnostic tools (signatures of stress or efficiency) and functional tracers (of movement or origin) that reveal the sources and pathways of water and nutrients. Linking environmental factors, soil properties, and tree species with isotopic tolls allows for more accurate predictions of soil health and provides the impetus for creating sustainable land management practices. This approach can also provide capacity-building and long-term planning opportunities to strengthen our ability to manage soils for optimal productivity and ecological health.

Nutrient cycling and ecological dynamics

Nutrient cycling is a fundamental environmental process that continuously influences ecological dynamics and plant growth and determines overall soil fertility. Stable isotopes are often utilized to investigate nutrient cycling in forest soils because they provide insights into how trees and soil microbes interact with nutrients across different spatial and temporal scales. Nutrient cycling in forest ecosystems is a dynamic and polymorphic process that has various influences. Anthropogenic factors, microbial activity, plant species composition, and seasonal patterns of nutrient uptake are only a few of the processes that can manipulate nutrient cycling. Stable isotopes offer influential means for disentangling these complexities that allow researchers to track the sources, pathways, and transformations of nutrients such as nitrogen, phosphorus, and carbon. They can function as integrative signatures of nutrient availability, loss, or accumulation in ways that were previously not possible. New viewpoints could lead to downstream improvements that make forest management practices more efficient in promoting soil fertility and ecosystem health (Table 3).

N assimilation is a fundamental tenet of nutrient cycling in temperate woodlands and is essential for the preservation of soil fertility and ecosystem productivity. Emerging ecological research often focuses on nutrient uptake during periods of dormancy. Ma et al. (2021) used $\delta^{13}C$–$\delta^{15}N$-labeled organic nitrogen in a δ^{15} isotopic tracing experiment to compare nitrogen uptake between evergreen and deciduous trees. In this

Table 3. Proportion of nitrogen found in different soil pools.

Soil pool	Total nitrogen (%)	Typical δ^{15}N range (‰)	Description	References
Ammonium (NH_4^+)	25%–40%	−3 to +3	Dominates in anaerobic or acidic conditions where nitrification is suppressed. δ^{15}N values depend on mineralization and microbial uptake dynamics.	Nadelhoffer et al. 1984; Wang et al. 2020*a*; Xu et al. 2021; Hu 2022; Park et al. 2023; Santesteban et al. 2024
Nitrate (NO_3^-)	10%–30%	+5 to +15	Prevails in well-aerated, neutral to alkaline soils. Enrichment due to nitrification and denitrification processes.	Wang et al. 2020*a*; Xu et al. 2021; Begum et al. 2022; Hu 2022; Li et al. 2022; Park et al. 2023; Santesteban et al. 2024
Organic nitrogen	40%–60%	−1 to +5	Largest pool of nitrogen, encompassing proteins, amino acids, and humic substances. δ^1N reflects balance between inputs (e.g., litter) and microbial decomposition.	Marty et al. 2017; Wang et al. 2020*a*; Xu et al. 2021; Hu 2022; Park et al. 2023; Toriyama et al. 2023; Santesteban et al. 2024
Dissolved organic nitrogen (DON)	5%–15%	+3 to +7	A subset of organic nitrogen, readily mobilized by water. Higher δ^1N due to active microbial turnover and leaching losses.	Philben et al. 2018; Wang et al. 2020*a*; Wang et al. 2021*a*; Xu et al. 2021; Hu 2022; Park et al. 2023; Santesteban et al. 2024
Gaseous nitrogen (N_2, N_2O)	<5%	+10 to +20	Produced during denitrification and volatilization. Highly enriched δ^1N due to fractionation during gas phase transitions.	Vallano and Sparks 2008; Wang et al. 2020*a*; Xu et al. 2021; Hu 2022; Park et al. 2023; Santesteban et al. 2024

study, δ^{15}N traced nitrogen uptake across seasons and showed that enriched tissue values reflected continued assimilation even while dormant. Both tree classifications continue to uptake nitrogen during the nongrowing season before finally cresting during late winter and prefer nitrogen in the form of NH_4^+. Shrubs and herbs prefer NO_3^-. Their work illustrated that nitrogen uptake is not limited to the growing season and stressed the importance of considering nutrient cycling across all seasons when assessing forest nitrogen dynamics. On the contrary, Gallarotti et al. (2021) researched nitrogen losses in tropical forest soils with a focus on nitrous oxide (N_2O) fluxes. Their study reported lower N_2O fluxes than expected, and the use of δ^{15}N, δ^{18}O, and qPCR determined that microbial reduction of N_2O to N_2 by denitrifying bacteria was responsible. Depletion in δ^{15}N and δ^{18}O of emitted gases indicated complete denitrification and reflected the preference of microbes for lighter isotopes during nitrate reduction. These isotopic shifts helped identify dominant nitrogen loss pathways and assess soil nitrogen retention. They emphasized the need for additional nitrogen cycling and alternative N-loss pathway studies in tropical soils.

N cycling fluctuated considerably across different forest types, such as in studies comparing uptake in temperate forests to that in tropical regions (Martinelli et al. 1999). Mao et al. (2024) investigated the dissimilar roles of δ^{15}N in soil N dynamics after nutrient addition and noted leguminous and nonleguminous forests were both δ^{15}N-depleted. Their study indicated that use of δ^{15}N as a source indicator where low values signaled active biological nitrogen fixation and minimal fractionation could detect distinct soil N dynamics between leguminous and nonleguminous forests. Legumes showed a greater ability to fix nitrogen and influence soil nutrient cycling than nonleguminous species, but understory species in leguminous forests had considerably higher δ^{15}N ratios. Lawson and Pike (2017) investigated variations in koa (*Acacia koa*) foliar δ^{13}C and δ^{15}N isotope ratios across 17 sites on Hawai'i Island that were categorized by elevation and precipitation gradients. Here, δ^{13}C indicated water use efficiency (WUE) by reflecting stomatal conductance and photosynthetic demand while δ^{15}N traced nitrogen source variation to reveal differences in nitrogen cycling and loss across gradients. Specific areas within the Waiakea Forest Reserve and Volcanoes National Park were noted where isotopic analyses suggested optimal conditions for reforestation efforts. These finding emphasizes the importance of plant functional types in shaping nutrient cycling and underscore the implications for forest management and restoration efforts in nitrogen-limited tropical ecosystems.

Additional studies on nutrient cycling in forest ecosystems have examined the slow uptake of key elements and emphasized the need for appropriate nutrient management strategies. Pistocci et al. (2020) addressed the link between microbial activity and soil phosphorus (P) dynamics in a temperate beech (*Fagus sylvatica*) forest with analyses of oxygen isotopic composition in phosphate δ^{18}O-P. As a tracer, δ^{18}O-P identified biologically cycled phosphorus versus mineral phosphorus by revealing isotopic shifts caused by microbial phosphate hydrolysis and exchange with soil water. They reported microbial P turnover influenced available P through hydrolysis and showed that δ^{18}O-P reaches equilibrium in P-rich soils but hydrolyzes in P-poor soils. For other nutrients, van der Heijden et al. (2015) used ^{26}Mg and ^{44}Ca to trace nutrient uptake and cycling in a 35-year-old beech stand on nutrient-poor, acidic soil. Their results revealed that most (~43%) Mg was collected from the leaf litter layer, while most (~42%) Ca was taken up from the top (0–5 cm). Here, isotopic tracers revealed how nutrient sources varied with depth and quantified vertical movement as well as root access to base cations. Uptake from deeper layers (15–70 cm) was minimal to negligible. They reported uptake of Mg and Ca was slow and asserted that nutrient pools were needed in nutrient-depleted ecosystems.

The costly effects of climate change on forest species also impact nutrient cycling and tree physiology. Lu et al. (2024) analyzed climate change impacts on the physiological and ecological processes of four tree species (*Pinus tabuliformis*, *Platycladus orientalis*, *Quercus variabilis*, and *Robinia pseudoacacia*) in a semi-arid region. They collected tree-ring $\delta^{13}C$ and intrinsic iWUE across 64 plots with different forest stand structures and site conditions and showed both increased over time in correlation with rising global CO_2 levels. Tree-ring $\delta^{13}C$ served as a long-term physiological indicator of water use efficiency, reflecting stomatal closure caused by rising CO_2 and drought stress. Their study showed coniferous species were more sensitive than broadleaf species, though both groups adapted to climate change.

Further research into this topic punctuates the need to grasp the pathways by which climatic factors influence soil processes in forest ecosystems. Miki and Doi (2016) looked at the response of leaf phenology and soil carbon dynamics to climate change with a late growth season–plant soil feedback (LGS–PSF) model. Their data indicated that microbe-mediated PSF will worsen the negative impacts of increasing temperature by increasing growth and activity. While not specific to a single isotope, combining $\delta^{13}C$ and $\delta^{15}N$ in future studies could better reveal microbial and plant feedbacks affecting resource cycling. They urge additional studies of CO_2 fertilization, water, and nitrogen availability, and microbial dynamics to be conducted as an extended growing season is expected to cause greater competition for nutrients among plants and microbes rather than increased productivity.

Soil carbon dynamics are integral to N cycling and are also intricately linked to nutrient cycling. Root production and microbial carbon inputs play critical roles in soil organic carbon (SOC) accumulation. Panchal et al. (2022) remarked that species with greater root exudation are important for the removal of atmospheric CO_2 and increasing the SOC content of forests and grasslands. Xiang et al. (2022) disclosed that mixed plantations increased SOC stocks by 12%, especially when the mixing proportion was below 55%. The type of mixed plantation was the main factor influencing these changes in SOC stocks. Additionally, mixed plantations on barren land showed the greatest potential for increasing SOC stocks compared to those on grasslands or croplands. Liu et al. (2022) presented a 14-year study of subtropical forests and showed how these factors work together to accelerate SOC accumulation during forest succession. It is typical for $\delta^{13}C$ to trace the origin and transformation of carbon inputs in this type of study. Rising SOC corresponds with shifts in $\delta^{13}C$ toward signatures characteristic of plant-derived carbon. Their research found that both root production and microbial carbon inputs drive the stabilization of SOC in early-successional stages, while leaf-derived carbon in late-successional forests may spur SOC decomposition. This emphasized the importance of biological processes in nutrient cycling during forest development and reiterated the need for further studies deploying $\delta^{13}C$. Studies pinpointing carbon dynamics in peat soils have further highlighted interactions between nutrient availability and carbon processes. The impact of forest drainage on carbon balance in nutrient-poor and nutrient-rich peat soils (Linkosalmi et al. 2023) indicates that nutrient-rich soils had higher respiration rates and that fresh carbon inputs suppressed peat decomposition most often in nutrient-poor soils.

Urban environments present additional challenges to nutrient cycling because of the significant degree of anthropogenic influences, such as traffic and air pollution. Gong et al. (2022) explored the isotopic composition of $\delta^{15}N$ and $\delta^{18}O$ in two urban forest sites, roadside and within a park, across different climate zones. This unique study investigated the impacts of roadside and park traffic exhaust by using $\delta^{15}N$ as a source signature to identify nitrogen from vehicle emissions. Elevated $\delta^{15}N$ levels at roadside sites showed that NOx from fossil fuel combustion was the primary input. Their study found that traffic exhaust had varying impacts depending on local humidity levels and significantly influenced nitrogen isotope signatures in urban forest areas. This can alter natural nutrient dynamics and influence tree growth and ecosystem health over time. The role of stable N isotopes in reconstructing terrestrial nutrient cycling has also been explored by Gerhart and McLauchlan (2014), who examined how $\delta^{15}N$ in wood can indicate historical nutrient dynamics. They used $\delta^{15}N$ to integrate past nitrogen availability. Higher values indicated periods of increased N deposition or loss through leaching or volatilization and provided insights into long-term nutrient cycling and its relationship with forest productivity. This study is especially important for gleaning additional data on how forests respond to shifts in nutrient availability, such as those caused by land-use changes or climate variations.

The speed and intensity of urbanization significantly influence forest health, nutrient cycling, and many other factors in urban ecosystems. McDermot et al. (2020) reported how urbanization intensity affected red maple tree (*Acer rubrum*) physiology and stress responses in two urban forests (Philadelphia, PA, and Newark, DE). Red maples displayed increased foliar chlorophyll, $\delta^{15}N$, nutrients, and stress-mitigating compounds such as free amino acids and polyamines after exposure to higher urban heat island effects, nutrient loads, and pollution. Here, $\delta^{15}N$ served as an urban pollution marker where elevated values indicated uptake of anthropogenic nitrogen and stress from altered nitrogen loads. The authors recommended red maples as biomonitors of urban forest health, as there were marked variations in nutrient and heavy metal concentrations between cities. These results suggested urban intensity could influence tree physiology and biochemical stress tolerance.

Soil carbon dynamics and forest microbial processes

Stable isotopes provide valuable insights into soil carbon storage and sequestration and the dynamics of soil erosion and sediment transport. Isotopic tracers allow for pinpoint accuracy when studying interactions between plant inputs, SOM, and microbial community inputs in forest soil research. These tracing methods augment our knowledge of carbon sources, transport, and long-term storage dynamics to aid in the development of climate change mitigation strategies.

Table 4. Soil organic carbon (SOC) distribution across different soil horizons in temperate forests.

Soil horizon*	Depth range (cm)	δ^{13}C Value (‰)	SOC (%)	References
O-horizon (Organic layer)	0–5 cm	−26.5	40%	Tefs and Gleixner 2012; Brunn et al. 2016; Gomez et al. 2020; Siqueira et al. 2020; Bai et al. 2021; Schneider et al. 2021; Liebmann et al. 2022; Neupane et al. 2022; Nordt and Holiday 2022; Alvarez et al. 2023; Behnke et al. 2023; Park et al. 2023; Wang et al. 2022*a*; Soldatova et al. 2024
A-horizon (Topsoil)	5–20 cm	−24.3	35%	
E-horizon (Leached layer)	20–40 cm	−23.1	12%	
B-horizon (Subsoil)	40–80 cm	−22.1	8%	
C-horizon (Parent material)	80+ cm	−20.5	5%	

*O-horizon; enriched in organic carbon with a more negative δ^{13}C value; reflecting active biological processes and plant carbon inputs at the surface; A-horizon; contains a mix of organic matter and mineral material with a less negative δ^{13}C value than the O-horizon; reflecting decomposition and microbial processing of carbon; E-horizon; may form in areas of higher rainfall or forested soils with leaching and contains less organic material but some carbon input from upper layers continues; δ^{13}C value reflects transition from more plant-derived carbon to mineral soil carbon; B-horizon; generally lower in organic matter as carbon in this layer has been more mineralized with a more positive δ^{13}C value; reflecting older carbon that is primarily microbial in origin; C-horizon; composed of weathered rock and minerals with very low carbon content; δ^{13}C value reflects that little organic matter remains in this horizon.

Forests play a vital role in carbon sequestration, but the ability of these ecosystems to store carbon is threatened by human activities, land-use changes, climate variability, and natural disasters. New strategies to protect these fragile areas and ensure forests remain carbon sinks are critically needed. Hurtt et al. (2019) used high-resolution remote sensing, field data, and ecological models to assess aboveground carbon stock. This effort uncovered a prominent gap between potential sequestration capacity and actual carbon levels that may be addressed with afforestation and reforestation. The study's comprehensive approach provides the wherewithal for improving state and regional carbon planning frameworks with an eye on future expansions.

In a broader context, Neupane et al. (2022) reviewed usage of δ^{13}C under global change factors including elevated CO_2 levels and land-use changes to deepen our understanding of SOC dynamics. They used δ^{13}C to trace the rate and source of organic matter inputs, with its enrichment or depletion linked to changes in photosynthesis pathways and decomposition patterns under environmental shifts. The collective opinion of most researchers was that cross-site modeling studies would improve predicted SOC under future environmental changes. An essential factor in enhancing carbon sequestration in forest soils is understanding the interactions between soil minerals and carbon. It is requisite to understand how the soil mineral structure alters or interferes with the stabilization of SOC. Porras et al. (2017) investigated the impact of pedogenic iron (Fe) and aluminum (Al) affect SOC stability in temperate forests. Their δ^{13}C analysis showed more negative values in mineral-rich soils. This indicated that newer organic matter was more effectively stabilized through organo-mineral associations that slowed microbial breakdown. They found that minerals like Fe and aluminum oxides (i.e., gibbsite ($AlOH_3$)) play a dominant role in stabilizing SOC by forming organo-mineral complexes that prevent microbial breakdown. Their δ^{13}C data indicated that soils with higher proportions of these linked minerals are superior for carbon storage. Ramesh et al. (2024) further emphasized the importance of environmental factors like microclimate and soil properties in shaping carbon dynamics. Their 3-year study of these relationships across 20 rainforest sites found that soil properties such as organic matter and C:N ratios generally increased with elevation while δ^{15}N decreased. As δ^{15}N was used to indicate nitrogen source and cycling strength, lower values reflected tighter nitrogen retention in high-elevation soils rich in organic matter. They stressed the use of bioclimatic and soil variables in climate change predictions for more accurate modeling of carbon dynamics.

Further insights into soil carbon dynamics come from studies examining the role of old-growth forests in carbon storage. A study by Tefs and Gleixner (2012) in an old-growth forest revealed carbon loss in the upper 0–20 cm soil layer with carbon and nitrogen accumulation in deeper layers. The δ^{13}C data attributed upper layer SOC loss and deeper layer gain to respiration and root-zone organic material. This pattern suggests root-driven carbon inputs greatly influence SOM across depths. This study reaffirms the expansive carbon storage potential of old-growth forests over long timescales.

Collectively, these findings underscore the value of isotopic analysis in advancing our understanding of carbon storage and sequestration in forest ecosystems. Stable isotopes offer strategic insight into understanding the complexities of the sources, storage, and long-term fate of SOC. Isotopic methods will continue to play a critical role in improving our understanding of soil carbon dynamics and informing strategies for carbon sequestration and climate mitigation as climate change accelerates (Table 4).

Microbial activity in soil is a cornerstone of nutrient cycling and plays a key role in soil respiration and ecosystem functioning. Soil respiration is driven by microbial CO_2 release during organic matter decomposition and is influenced by microbial community composition, substrate availability, and environmental conditions. Recent discoveries have enhanced our understanding of the microbial and root mechanisms driving soil respiration and the ways these contribute comprehensively to broader soil dynamics.

The quality of plant litter and microbial dynamics significantly influence soil respiration. Fast-decaying litter can stimulate microbial activity by providing labile substrates that enhance soil respiration. Craig et al. (2022) used δ^{13}C and δ^{18}O

to study litter decomposition and found that rapid turnover of organic matter increases microbial activity and soil respiration rates. Less negative $\delta^{13}C$ in respired CO_2 served as a tracer indicating microbial mineralization of fresh litter and showing increased decomposition activity. This effect was not linked to microbial physiological traits. Lyu et al. (2019) conducted a 4-year study on litter inputs and remarked that $\delta^{15}N$ increased with litter input and total soil nitrogen decreased by 26% with no change to SOC in rooted plots. The $\delta^{15}N$ isotope served as a signature of nitrogen transformations with higher values showing greater mineralization and loss of lighter nitrogen isotopes through leaching or gas emissions. No fluctuation in SOC or N was observed in root-free plots. The interplay between plant roots and microbial communities is often interpreted and simplified through root decomposition studies. Herzog et al. (2019) performed a 2-year study of root decomposition in a Scots pine (*Pinus sylvestris*) forest. They used $\delta^{13}C$ and $\delta^{15}N$ to trace chemical changes under dry and irrigated conditions and found initial decomposition involved fast-growing taxa (e.g., *Bacteroidetes* and *Helotiales*), and the later stages were dominated by specialized decomposers like *Acidobacteria* and lignin-decomposing fungi. They concluded that microbial communities exhibited functional redundancy as decomposition rates remained steady regardless of microbial composition. This suggests that microbial diversity ensures stable soil processes. Studies of microbial functional community attributes rather than taxonomic composition are necessary for understanding soil processes like respiration and nutrient cycling. Chen et al. (2020) argued that functional traits are the foundation of soil process regulation. Traits such as functional gene abundance spur denitrification, nitrification, and soil respiration and convey a need to develop functional gene-based frameworks into predictive biogeochemical models to address biodiversity loss impacts.

Priming effects have been a major focal point in studies of soil respiration because they directly influence decomposition rates and microbial processes when triggered by the addition of fresh materials. Kuzyakov et al. (2000) highlighted how microbial communities in soils respond to changes in substrate availability and proposed methods for quantitatively studying priming effects and their dynamics with $\delta^{13}C$ and $\delta^{15}N$, in addition to nonisotopic techniques. In priming studies, $\delta^{13}C$ labels new inputs so that unlabeled CO_2 reveals native SOC mineralization. This distinction helps identify how fresh additions trigger decomposition of existing soil carbon. Their review showed that fresh substrate additions can accelerate the decomposition of stable organic compounds and microbial redundancy, helping maintain ecosystem stability. Redundancy is the ability of different microbial taxa to perform similar functions to ensure processes like respiration and nutrient cycling are preserved even when specific microbial groups are disrupted. Jin et al. (2024) reassessed the regulatory gate hypothesis and discerned that microbial functional redundancy ensured soil ecosystem stability despite disturbances, and pathways like soil respiration and nutrient cycling were preserved.

Environmental factors such as precipitation significantly influence microbial activity and decomposition rates. Greenlon et al. (2022) combined quantitative stable isotope probing (qSIP) with $H_2{}^{18}O$ labeling to track soil microbial activity across three grasslands with differing historical precipitation. The $H_2{}^{18}O$ served as a tracer of active DNA synthesis, enabling precise identification of microbes growing in their natural environment. They found that higher precipitation was linked to heightened growth and activity of motile soil microorganisms, while decomposition capacities, methanol oxidation, and CO levels were not significantly changed. These findings underscore the complexity of how precipitation affects microbial dynamics in different ecosystems. Soil microbial growth rates have also been studied by Caro et al. (2023) in hydrogen stable isotope probing experiments. The authors examined microbial growth in soils using $\delta^{13}C$ and $\delta^{15}N$ and observed how isotopic ratios in microbial biomass reflected slow rates of assimilation. This suggests a physiological limit on growth despite carbon substrate availability. Their data aligned with other studies, indicating that soil microbial growth is slow even when carbon substrates are readily available. Alongside precipitation, soil pH is another critical factor shaping microbial function. Ontman et al. (2023) explored the relationships between soil pH, microbial biomass, and microbial activity in a northern hardwood forest. Their findings revealed that pH influences microbial functions more intricately than previously understood and suggested that low pH levels could drive nitrogen cycling adaptations, while higher pH levels stimulate mycorrhizal associations. Changes in $\delta^{15}N$ values at different pH levels indicated shifts in nitrogen transformation pathways and reflected a microbial preference for ammonium (NH_4^+) to nitrate (NO_3^-). These findings emphasized the need for a nuanced approach to studying environmental regulators of microbial processes to accurately interpret soil respiration data (Table 5).

Temperature has also been a well-studied environmental factor related to soil respiration. Soil respiration rates are influenced by C:N ratio, DOC content, and soil pH and increase with temperature. Klimek et al. (2021) compared soil respiration sensitivity to temperature across seven temperate forests and found increased temperature led to higher respiration rates. The most significant respiration increase was in the O horizon of hornbeam (*Carpinus betulus*) dominated forests. A rise in temperature was nonsignificant across forest types despite variation in soil respiration rates. The interaction between root-derived phenolics and microbial activity can also modulate soil respiration. Zwetsloot et al. (2020) found that root phenolic compounds directly influenced microbial composition and increased soil respiration by priming microbial decomposition. Their $\delta^{13}C$ tracer study showed that 1° and 2° root metabolites mediate soil biogeochemistry in nutrient-limited ecosystems where shifts in microbial communities resulted in increased soil respiration, though responses to nutrient additions varied. This varying response to nutrient additions was also reported by Weng et al. (2020) who showed biochar reduced SOC mineralization by nearly 48% while improving nitrogen use efficiency and by Zhang et al. (2021*a*) who posited nutrient inputs influence nitrification and denitrification pathways when regulating soil respiration.

Table 5. Relationship between soil pH and isotopic discrimination of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$).

Soil pH range	Depiction	Effect on $\delta^{13}C$ (‰)	Effect on $\delta^{15}N$ (‰)	Underlying mechanisms	References
<4.5	Strongly acidic	May slightly decrease (<−27)	Lower values (<1)	Suppressed microbial activity limits decomposition and nitrogen cycling, reducing isotopic fractionation.	Peri et al. 2012; Cornwell et al. 2018; Li et al. 2018; Shtangeeva et al. 2019; Konstantinov et al. 2023; Medriano et al. 2023; Gao et al. 2024; Liu et al. 2025
4.5–5.5	Moderately acidic	Remain low (−27 to −26.5)	Slight increase (1–3)	Decomposition begins to accelerate, leading to slight $\delta^{15}N$ enrichment from nitrogen mineralization.	
5.5–6.5	Slightly acidic	Slight increase (−26.5 to −25.5)	Moderate enrichment (3–6)	Optimal microbial activity enhances organic matter decomposition and nitrogen cycling, increasing $\delta^{15}N$ values.	
6.5–7.5	Neutral	Stabilized (−25.5 to −24.5)	Highest point (6–8)	High microbial efficiency and mineralization enrich $\delta^{15}N$ through denitrification and ammonia volatilization.	
7.5–8.5	Slightly alkaline	Increases (−25 to −24)	Fully stabilized (5–7)	Reduced microbial efficiency may limit further $\delta^{15}N$ enrichment; carbonate weathering may influence $\delta^{13}C$.	
>8.5	Strongly alkaline	Remains stable (−25 to −24)	Slight decrease (<5)	Ammonia volatilization reduces nitrogen availability, lowering $\delta^{15}N$.	

The evolving research methodologies surrounding stable isotope and functional trait analyses are pivotal strategies for studying the fundamental but multifaceted mechanisms of microbial activity and soil respiration. Isotopes serve as source indicators like $\delta^{13}C$ for plant versus microbe-derived carbon, process tracers such as $\delta^{15}N$ for nitrification and denitrification, and activity proxies like ^{18}O in qSIP, to help clarify underlying mechanisms across varied conditions. Synergistic linkages between microbial communities in conjunction with their forest soil environment govern soil metabolic activity. These insights inform strategies for improving soil health and enhancing ecosystem resilience.

Tracing pollutants and sediment transport in forest soils

Studies of forest soil pollutant dynamics in response to climate change, ecosystem restoration, or urbanization represent a vital field of research. Using stable isotopes to improve our comprehension of the correlations between pollutants and soil properties offers a promising approach to managing forest soil health and mitigating the impacts of pollution in both natural and anthropogenically influenced environments. Early research showed that isotopic tracers can follow pesticide movement through soils and biota (Peterle 1966) and provided the basis for modern pollution tracking. The persistence of some pollutants in forest soils is influenced by complex interactions between anthropogenic deposition, soil composition, and biological processes. The interactions between these elements become crucial in understanding how contaminants persist and affect ecosystems as pollution sources vary. The presence of waste materials in soils has implications for ecosystem health and forest restoration. Walters et al. 2010 emphasized the need for field-based risk assessment and consideration for chronic exposure after noting that many pharmaceiticals and personal-care products (PPCPs) in biosolid-ammended soils persist for years due to limited bioavailability and co-contaminanats. Masinga et al. 2024 reviewed how emerging organic contaminants (EOCs) like PPCPs, plasticizers, flame retardants, and PFAS move, transform, and bioaccumulate in the soil–plant–receptor continuum where they pose ecological and human health risks. Stable isotope studies enhance our understanding of these dynamics by providing key insights into the sources, transformations, and fate of contaminants in soil environments.

Stable isotope studies have enhanced our understanding of the fate and transport of pollutants in forest soils and shallow groundwater. Isotopic tracers such as $\delta^{15}N$ and $\delta^{18}O$ help distinguish between nitrate derived from atmospheric deposition, manure, and synthetic fertilizers (Kendall et al. 2007). This means $\delta^{15}N$ serves as a signature and tracer where higher values indicate manure or denitrification and lower values suggest fertilizer or atmospheric inputs. Shallow groundwater nitrate carries $\delta^{18}O$ signals from water and atmospheric oxygen due to nitrification and shows minimal input from denitrification. Wei et al. (2024) used these markers to reveal that nitrate pollution is closely linked to land use with the highest concentrations are found in cultivated and urban areas where fertilizers and sewage are primary contributors. Forested lands were mainly affected by atmospheric deposition and fertilizers. Analysis of both $\delta^{15}N$ and $\delta^{18}O$ allows researchers to track pollution pathways, identify source mixing, and locate areas of diminished nitrate. These insights are vital for understanding impacts on soil and water quality.

Mercury (Hg) contamination is a critical focus of isotopic studies in forest ecosystems as they complement research into pollutants like polycyclic aromatic hydrocarbons (PAHs). Forests mediate Hg deposition (2200–3400 Mg/year estimated) with vegetation such as moss and lichen being pivotal to Hg uptake (Jiskra et al. 2019). This highlights how forests regulate Hg cycling and how factors such as climate change, deforestation, land-use change, and wildfires are increasing Hg emissions. Isotopic analysis of Hg, using

mass-dependent and mass-independent fractionation has proven effective in tracing human-related inputs and natural cycling in forest soils (Jiskra et al. 2019). Mercury isotopes act as signatures of industrial, atmospheric, or natural sources, with distinct isotope patterns identifying emissions from coal combustion or artisanal gold mining. These ratios also reflect microbial and photochemical processes that influence mercury mobility and bioavailability. Environmental conditions like redox state, organic matter levels, and microbial activity alter isotope behavior and shape the values observed. Jiskra et al. (2019) also showed that aboveground vegetation captures gaseous elemental mercury in the Arctic tundra and stores about 70% of atmospheric Hg in plants and soils that later release it into aquatic systems. Graydon et al. (2009) used ^{199}Hg and ^{200}Hg to study Hg uptake and retention by boreal forest plants. Wang et al. (2022*b*) reviewed Hg isotopic fractionation studies of forest soils to better understand its transport and transformation. Their findings revealed that plants primarily absorb Hg(II) from the atmosphere and enhanced our understanding of Hg accumulation, cycling, and retention in forest ecosystems.

The value of heavy metal isotopes such as copper (Cu), lead (Pb), and zinc (Zn) for tracing the sources and movements of contaminants in polluted soils near mining and smelting sites is well-established. Aranda et al. (2012) used zinc isotopes (δ^{66}Zn) to study zinc behavior in surface and pore waters within a mountain watershed affected by acid rock drainage and found that lighter zinc isotopes were more easily mobilized during sulfide mineral weathering. This indicates kinetic fractionation during early mineral dissolution and supports the use of zinc isotopes as tracers of both natural and human-driven zinc inputs, particularly where pH and redox conditions shift. Gelly et al. (2019) studied legacy pollution in soils near a decommissioned Pb-Ag (lead-silver) smelter in France. They traced Cu, Pb, and Zn redistribution across the soil profile more than 100 years after smelter operations ceased. Their isotopic and elemental analysis showed continued enrichment of metals at depth. Lead isotope ratios clearly pointed to smelter-derived pollution, even several kilometers downwind. These findings show that Pb isotopes can reliably trace industrial contamination and reveal how long such pollution can persist in forest soils. Souto-Oliveira et al. (2018) used the isotopic signatures of Cu, Pb, and Zn in urban aerosols to distinguish between natural dust, vehicle emissions, and industrial sources. Although their study focused on aerosols, the results are relevant to forest soils downwind of urban areas or smelting sites. They showed that distinct isotope patterns distinguish metal contributions from different sources. This helps clarify contamination scenarios and supports better remediation planning.

In a mining region, Kříbek et al. (2018) examined copper isotope variation (δ^{65}Cu) in soils and grasses near smelting operations in Tsumeb, Namibia. They found clear isotopic differences between uncontaminated soils and those affected by industrial Cu. Plants growing in contaminated areas showed Cu isotope values that matched the polluted soils. This pattern confirms that isotope fractionation occurs during plant uptake and supports the use of Cu isotopes as tracers of contamination and biological processing. Liu et al. (2020) used δ^{66}Zn isotopes to track zinc movement in paddy soils near a mining area in China. They identified enrichment patterns that followed both vertical and lateral migration, shaped by redox cycles and organic matter interactions. Their findings showed that isotope ratios can reveal both the source and the transformation of metals. This makes Zn isotopes useful tools for understanding how zinc moves through and remains in agricultural soils impacted by mining.

Studies on specific heavy metals provide valuable insights into their behavior and impact information regarding the dynamics of pollutants. Mining activities release contaminants that hinder natural recovery of forest ecosystems. Such contamination poses significant challenges for ecosystem restoration activities when the interactions of pollutants with soil properties are considered. Mine tailings are the waste materials left over after the extraction of valuable metals or minerals from ore and typically consist of crushed rock, water, and expended chemicals. Araújo et al. (2024) used mine tailings to simulate varying contamination levels for Deguelia costata (*Deguelia costata* Benth.) and yellow poinciana (*Peltophorum dubium*). Both species proved acceptable for restoration by thriving in 100% tailings, but lower concentrations prompted higher organic matter and acidity, while higher concentrations boosted biomass and seedling quality and generated toxic metals that plants could not absorb. Metal absorption was heightened in the acidic reference soil, causing reduced growth and increased antioxidant enzyme and flavonoid production. The size of soil particles significantly influences pollutant mobility and bioavailability. Soil particle size influences heavy metal distribution, with smelting sites often contaminating nearby soils with As, Cd, Cu, Hg, Pb, and Zn, threatening groundwater and human health. The size of soil particles influences their mobility and bioavailability and directly affects how pollutants interact with and move through the soil. Zhao et al. (2024) examined heavy metal distribution at an abandoned smelting site and detailed how particle size fractionation in soils influenced pollutant mobility and bioavailability. These findings suggest that tailored remediation strategies that include particle size considerations are needed to address the widespread problem of soil contamination.

Stable isotopes can track related aspects of pollution to discover its effect on nitrogen cycling in forest ecosystems. Chaschina et al. (2018) reported that flora in forest soils with arbuscular mycorrhizae near a Cu smelter had higher δ^{15}N values. This study adds to the growing body of evidence showing how specific pollutants, such as Cu, can significantly alter nitrogen cycling in forest soils. They linked this phenomenon to deeper root systems and limited mycorrhizal formation. The δ^{15}N ratio within leaves of certain species from the polluted area was 2.8–3.3‰ higher than in unpolluted forests and indicated Cu induced significant changes in nitrogen cycling. These isotopic changes in nitrogen and carbon can be compared with other heavy metal pollution studies to expand our comprehension of pollutant effects on ecosystem function. Rijk and Ekblad (2020) used δ^{13}C and δ^{15}N and microbial assays to investigate Pb contamination in a polluted grassland. The presence of Pb reduced microbial activity, slowed

nutrient cycling, and led to increased soil C:N ratios and SOM accumulation. The ecosystem exhibited signs of adaptation despite the occupancy of Pb, though this tolerance came at a cost.

Recent studies have explored how elements such as cadmium (Cd) interact with plants under different atmospheric conditions. For instance, Huang et al. (2024) conduced a $\delta^{13}C$ tracing experiment to investigate the effects of elevated CO_2 (eCO_2) on phenolic compounds in black locust (*R. pseudoacacia* L.) seedlings exposed to Cd pollution. This study explores the interactions between atmospheric carbon enrichment, heavy metal contamination, and plant physiological responses. The results indicated how interactions can alter plant physiology and soil chemistry. Their findings indicated eCO_2 and the AMF *Funneliformis mosseae* (FM) enhanced phenolic acid and flavonoid synthesis, which bolstered Cd stress resistance and promoted phytostabilization in Cd-contaminated soils.

Urban pollution and its impact on plant health has also been examined using stable isotope techniques alongside CO_2 and Cd interactions. Soba et al. (2021) reported that $\delta^{13}C$ and $\delta^{15}N$ in Littleleaf Linden (*Tilia cordata*) leaves could accurately trace impacts of urban pollutants such as Pb, Cr, and Cd, with the greatest concentrations linked to traffic emissions. Alongside this work, other studies have demonstrated how pollutant-induced changes in carbon and nitrogen cycles can serve as key indicators of environmental stress. Manninen et al. (2022) illustrated how SO_2 and NO_x pollution impacts boreal forest trees and soil nitrogen cycling. Emissions from a Ni-Cu smelter elevated $\delta^{13}C$ in evergreens like Scots pine (*P. sylvestris*), which reflected stomatal changes and water stress. Increased $\delta^{15}N$ in both evergreen and deciduous species revealed NO_x uptake and disrupted soil nitrogen cycling. These groups demonstrated how $\delta^{13}C$ and $\delta^{15}N$ research studies could be key in the biomonitoring of pollution levels, as both studies found significant correlations between pollutant concentrations and isotopic signatures in plant tissues.

Cadmium isotopes such as $\delta^{114}/^{110}Cd$, are often used to trace contamination source behavior in soils and soil–plant systems. Cloquet et al. (2006) showed that surface soils near a Pb–Zn refinery in France showed distinct δCd values that helped differentiate industrial, agricultural, and slag-derived Cd after Pb isotope data were inconclusive. Similarly, Gao et al. (2022) found that heavier cadmium isotopes ($\Delta \approx +0.08$ to $+0.18$‰) became more enriched at greater soil depths in mining areas of southwest China. This pattern was linked to associations with free iron and manganese oxides and illustrated the downward migration of ore-derived contamination.

Laboratory studies revealed that Cd isotope behavior reflects mineral type. Iron oxides preferentially adsorb lighter isotopes ($\Delta \approx -0.51$ to -0.55‰) and structural substitution can enrich heavier ones ($\Delta \approx +0.22$‰). Wasylenki et al. (2014) showed that cadmium adsorption to manganese oxyhydroxides preferentially incorporates lighter Cd isotopes, with fractionation slightly influenced by ionic strength. Yan et al. (2021) demonstrated that adsorption of Cd onto iron (oxyhydr)oxides favors lighter isotopes and substitution into the iron mineral lattice enriches heavier isotopes thus indicating distinct fractionation depending on binding mechanism. Xu et al. (2025) found that montmorillonite and kaolinite favor adsorption of lighter Cd isotopes ($\Delta \approx +0.03$‰) based on mineral structure rather than pH or ionic strength controlling fractionation. These findings demonstrate that δCd can identify pollution sources, track vertical movement in soils, and explain mineral-driven retention processes—making cadmium isotopes a valuable tool for environmental tracing in contaminated forest and mining landscapes.

The reliability of stable isotopes in tracing the origins and transformations of specific pollutants like PAHs has become increasingly important in environmental contamination monitoring (Fig. 2). Gao et al. (2018) reviewed PAHs that are widespread environmental contaminants with carcinogenic and mutagenic properties. They noted that soil PAHs can be traced with $\delta^{13}C$ to uncover biogenic, petrogenic, and pyrogenic sources and suggested a mechanism for connecting $\delta^{13}C$ values to the way PAHs cycle in the environment that recognizes the challenges of specialized equipment needs and a lack of standard sample preparation. They urged that creating a database of isotopic signatures could aid in accurately identifying PAH sources and how PAHs transform in soils.

Sulfur isotopes ($\delta^{34}S$) help trace the origins of sulfate pollution and how it moves in forest soils. Novák et al. (2005) analyzed $\delta^{34}S$ within 13 forest catchments in Central Europe and found that historically heavily polluted sites still release stored anthropogenic sulfur while cleaner sites continue to accumulate it. This supports the conclusion that organic cycling in soil, rather than bedrock weathering, drives sulfur retention and release across a wide range of pollution levels. Isotopic signals for sulfate linked to fossil fuel burning varies from that of natural sources. Clear differences are noted between human and natural sulfur inputs when $\delta^{34}S$ acts as a source marker. Lower values typically denote industrial pollution and higher values suggest marine or rock-based sulfur. These signals vary depending on distance to the pollution source and how much biological processing has occurred. Changes in $\delta^{34}S$ values caused by soil acidification and microbial activity provide additional insight into how pollution alters sulfur cycling.

Studies on specific heavy metals, such as nickel (Ni), offer valuable insights into pollutant dynamics. Paul et al. (2021) investigated the biogeochemical cycling of Ni and trace elements like Co, Mn, and Zn in a tropical rainforest dominated by the hyperaccumulator tree *Pycnandra acuminata* that can absorb 25 wt.% Ni in its latex. They used a $\delta^{60}Ni$ analysis to ascertain the biotic origins for Ni in upper soil layers and *P. acuminata* shoots, which insinuated that a complex transport mechanism led to absent litterfall phytoenrichment. Further investigations into the responses of forest plants to heavy metal emissions have revealed additional isotopic evidence of altered nutrient cycling. Veselkin et al. (2022) used $\delta^{13}C$ and $\delta^{15}N$ to examine forest plants exposed to heavy metal emissions from a copper smelting plant. They found $\delta^{15}N$ increased 2–3.5‰ in foliage near the plant, an indication of altered nitrogen uptake, while $\delta^{13}C$ ratios remained stable. Functional groups like ECM trees and herbs with AM mycorrhiza also showed notable isotopic changes. These findings

Fig. 2. Overview of how isotope tracers are used to study sediment transport.

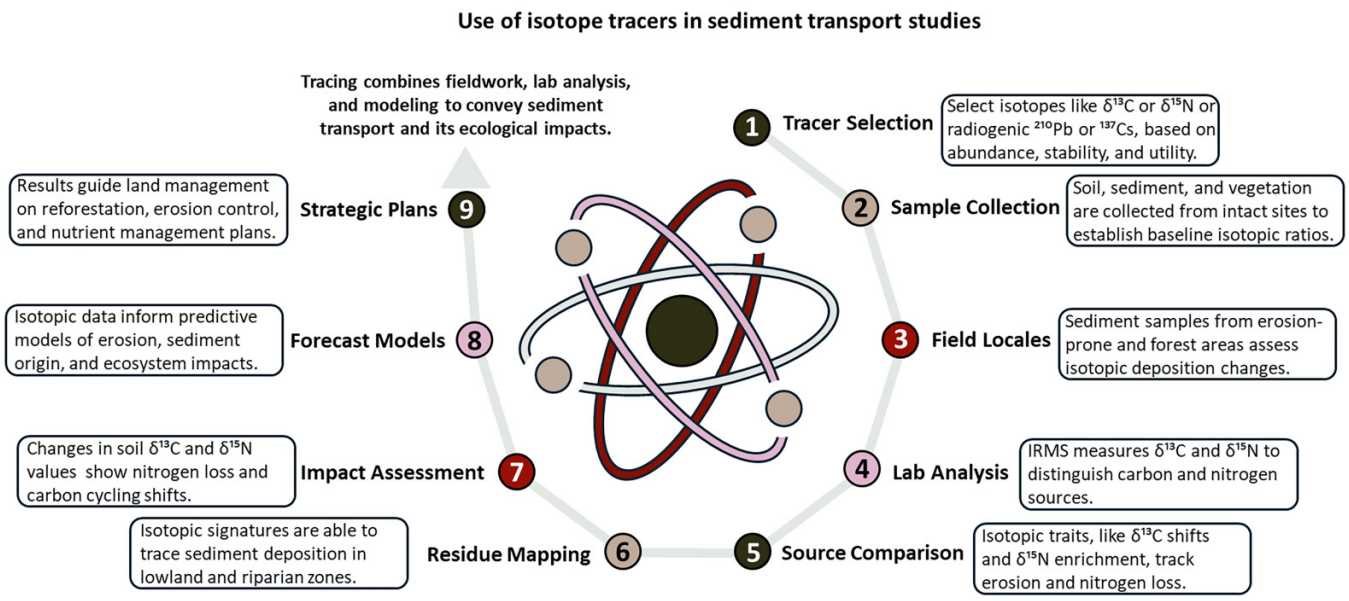


Table 6. Shifts in δ^{13}C and δ^{15}N values due to soil erosion over time in forested areas.

Time (years)	δ^{13}C (‰)	δ^{15}N (‰)	Description	References
0	−27.0	5	Baseline values, rich topsoil	Zollinger et al. 2015; Gomez et al. 2020; Wang et al. 2020*b*, 2022*a*; Nordt and Holiday 2022
10	−26.5	6	Slight topsoil loss	
20	−25.8	6.8	Increased erosion; reduced organic matter	
30	−25.3	7.5	Subsoil influence; δ^{13}C enriched	
40	−24.9	8.2	Severe erosion; higher δ^{15}N due to organic loss and deeper nitrogen cycling	
50	−24.5	8.8	Persistent subsoil exposure; isotopic enrichment stabilizes	

highlight the impact of heavy metal emissions on isotopic composition and nutrient cycling in polluted ecosystems.

Pollution and urbanization intensity can significantly influence tree physiology in urban forests. McDermot et al. (2020) reported how urbanization intensity affected red maple tree (*Acer rubrum*) physiology and stress responses in two urban forests (Philadelphia, PA, and Newark, DE). Red maples displayed increased foliar chlorophyll, δ^{15}N, nutrients, and stress-mitigating compounds such as free amino acids and polyamines after exposure to higher urban heat island effects, nutrient loads, and pollution. The authors recommended red maples as biomonitors of urban forest health, as there were marked variations in isotopic signatures linked to local environmental changes.

Environmental pressures from pollution and land-use changes affect not only plant physiology but also broader ecosystem functions like soil stability and nutrient retention. Urbanization and industrial emissions alter isotopic signals in vegetation and can intensify soil degradation and erosion. These linked impacts highlight the importance of examining belowground responses like root dynamics and soil structure to fully grasp resulting ecological changes. Stable isotopes can trace sediment movement, identify erosion sources, and evaluate how vegetation contributes to erosion control across forested and urban landscapes.

Soil erosion and the consequent sediment redistribution are key processes influencing landscape dynamics, soil fertility, and global ecosystems. A solid understanding of these finely-balanced and interconnected processes is particularly important in regions where human-induced land-use changes and climate variability have intensified erosion and degraded soil quality. Recent research utilizing stable isotopes offers new perspectives into the effects of soil erosion on ecosystem functioning while shedding light on sediment fluxes and the sources of eroded materials (Table 6).

Stable isotope applications can now integrate with biomarkers to trace the fate of specific compounds, organisms, or degradation processes. CSIA, stable isotope probing (SIP), and DNA-SIP effectively link contaminant transformation to microbial activity and identify pollutant sources in terrestrial and aquatic systems. Oakes (2017) demonstrated how CSIA tracks biomarkers using δ^{13}C values of PAHs, fatty acids, and sterols to reconstruct contaminant pathways. Oakes linked isotope values to molecular structures to

distinguish biomarkers from fossil fuels and natural sources and to track their transformation during transport. The ISOTOPEST database (Masbou et al. 2024) provides baseline $\delta^{13}C$ and $\delta^{15}N$ signatures for many commercial pesticides and provides CSIA reference values for distinguishing between degradation and source variability in forest and soil systems. Madsen (2006) reviewed the use of SIP in bioreactors and field studies where ^{13}C-labeled contaminants are tracked through microbial DNA or RNA. This method identifies active degraders and measures biotransformation to reveal microbial roles in pollutant removal from forest and riparian zones. Jiang et al. (2015) used DNA-SIP to isolate phenanthrene-degrading bacteria from contaminated soils and discovered novel taxa involved in PAH breakdown. They applied ^{13}C-labeled phenanthrene to identify previously uncultured degraders. This technique connects isotopic signals to microbial identity and function and explains pollutant removal in forest soils undergoing remediation or chronic contamination. More recently, Kim et al. (2023) used stable and radioactive isotopes to study natural attenuation of phenol in forest soil after a chemical spill. They showed that $\delta^{13}C$ values of residual phenol and ^{14}C dating can distinguish recent contamination from legacy inputs. This dual-isotope method provides a forensic tool for source attribution when organic signals overlap while SIP enhances tracing by linking labeled substrates directly to microbial degraders.

Recent studies have explored the effectiveness of tree root systems in soil stabilization to better understand the dynamics of soil erosion. Other studies highlight the role of tree root dynamics in combating soil erosion and degradation. Benavides-Tocarruncho et al. (2024) investigated tree root dynamics in a degraded tropical dry forest. They found no collaboration between species in nutrient uptake or soil stabilization. The study emphasized that thick roots are effective for restoration in compacted soils, and thin, branched roots perform better in less dense soils. Root traits like diameter and branching influence a species' ability to thrive in specific soils and reiterate how appropriate species selection is to soil restoration. This insight is crucial for updating forest management practices aimed at reducing soil erosion in degraded landscapes and provides specifics of how different tree species contribute to soil stabilization and erosion control.

Forest restoration efforts now use technological advances such as UAV-supported seed sowing (UAVsSS), which shows promise for addressing soil erosion and improving ecosystem resilience. Mohan et al. (2021) described the implementation of UAVsSS for afforestation and reforestation projects that address desertification, flooding, and soil erosion. They noted UAVsSS was cost-effective and easily deployed in difficult terrain, but faced challenges like accuracy, seed survival, and weather conditions. They concluded that the method would best be deployed in conjunction with traditional methods, environmental policies, and carefully considered species selection.

SOM plays a significant role in soil health and erosion mitigation in addition to tree root dynamics. Degraded soils typically have lower SOM volumes. Siqueira et al. (2020) used tree biomass from 33 forest tree species and SOC to track recovery in soils recovered with agroforestry systems (AFS), AFS could improve SOC sequestration and potentially promote soil restoration to mitigate some erosion effects in degraded soils, but they have no direct influence on carbon storage in soil or tree biomass. This stresses the necessity of land management measures in soil remediation efforts.

Understanding how sediment flux impacts soil erosion is as vital as recognizing the necessity of organic matter. Liu et al. (2021) reviewed models of SOM in eroding landscapes and underscored the challenges of quantifying sediment fluxes and the associated organic carbon content. They concluded that the use of compound-specific stable isotope analysis (CSSI) in conjunction with inter-comparable models is a promising new approach to trace and quantify SOM fluxes in soil erosion and provide insight into the contribution of various land-use types to sediment loads. This is particularly important in efforts involving $\delta^{13}C$ and $\delta^{2}H$. Their work emphasized the need for better models to understand processes essential for improving soil conservation and fertility strategies and mitigating the impacts of erosion on SOM transport and sediment dynamics.

Predictive models used for forest recruitment and adaptation to climate change can provide valuable insights for use in soil and ecosystem management strategies. Wang et al. (2023*a*) emphasized developing climate-sensitive nonlinear mixed-effects models to predict oak (*Quercus* spp.) recruitment in degraded secondary forests using data from 548 sample plots. Key factors influencing recruitment included stand basal area, quadratic mean diameter, basal area of the species, slope, elevation, and MAT. The inclusion of regional random effects significantly improved model accuracy and enhanced the applicability of these models for adaptive management strategies and forest composition predictions under climate change scenarios.

Innovative approaches to forest degradation and climate change management are also key to improving soil erosion resilience. Fajardo et al. (2022) studied forest degradation in a temperate evergreen forest using multivariate analysis and machine learning to assess forest attributes such as tree density, species richness, and soil nutrients. Their data identified thresholds such as <200 trees/ha and five or more exotic species for inclusion in climate change forest health management guidelines.

Other studies have complemented these findings by examining the role of nutrients and nutrient cycling and their link to erosion within forest ecosystems. Uhlig et al. (2017) utilized ^{26}Mg to quantify nutrient uptake in a temperate forest landscape as a driver of rock weathering in forest ecosystems. Concentrations of certain essential elements (Ca, K, Mg, and Si) were linked to soil weathering and erosion processes, with a substantial portion (50%–100%) of Mg released by weathering being taken up by forest trees. Many nutrients were exported via plant litter and coarse woody debris rather than being recycled. Thus, rapid weathering and soil degradation can lead to long-term impacts on forest productivity and stability.

Understanding nutrient transport within vast river basins has also proven valuable in tracing sediment sources and their impact on ecosystems. Charbonnier et al. (2020) ex-

plored the role of biological cycling in the rock-derived nutrient accumulation of barium (Ba) in the Amazon River basin to trace sediment transport. They used (δ^{138}Ba) from river samples to support their theory that biological processes alter Ba levels. This work demonstrated how stable isotopes can serve as powerful tracers for understanding nutrient cycling in large catchments.

Techniques for tracing sediment sources have advanced through the aid of fallout radionuclides, which offer a deeper understanding of biological cycling. Fallout nucleotides are typically described as nucleotides with mutations or structural changes resulting from exposure to radiation from nuclear fallout. Laceby et al. (2015) utilized low fallout radionuclide concentrations (^{137}Cs and ^{210}Pbex) to generate sediment provenance analyses of channel and gully erosion. Their research revealed that erosion of channel banks provided much more sediment than previously modeled. They cautioned using δ^{13}C and δ^{15}N for provenance analysis because they are biologically reactive and emphasized the importance of accurately tracing sediment sources in agricultural landscapes where unchecked erosion can lead to significant shifts in soil quality and composition. The development of new mixed models or tools to model the concentration-dependent behavior of these isotopes alongside radionuclides and sediment geochemistry.

These studies underscore the complexity of soil erosion and sediment transport while highlighting the growing potential of stable isotopes to provide critical insights. They demonstrate the increasing precision of metal isotopes for distinguishing sources, pathways and transformations of contaminants in forest soils, mining landscapes, and urban fringes. Ongoing refinements of existing methods and models can improve our ability to predict and manage soil erosion impacts on ecosystem function and soil quality. These insights are key to designing more effective soil conservation and land restoration strategies. Stable isotope analysis plays a central role by helping scientists identify pollution sources and trace pollutant movement through forest soils. Researchers can more accurately describe the environmental fate of pollutants by using isotopes as tracers and signatures.

Innovative methods and forward trends in soil isotope analysis

Recent advancements in isotopic analysis have introduced new and more innovative tools to aid soil carbon dynamics studies of forest ecosystems. One such development is the use of compound-specific stable isotope analysis (CSIA). This provides a fine-scale view of SOC fluxes by identifying isotopic signatures of individual organic compounds that act as tracers to determine specific carbon source contributions to total SOC pools. This method offers pointed insights into how different carbon sources such as root exudates and microbial biomass contribute to long-term sequestration and could be integrated with traditional isotopic methods for additional detail. The use of CSIA has increased in studies of SOM turnover and root-derived carbon to enhance forest management practices (Zhong et al. 2024). CSIA can be integrated with traditional bulk soil isotope methods to create a more detailed carbon budget at the site-specific level to improve carbon flux modeling and predictions. Additionally, CSIA and related isotope tracer approaches such as stable isotope probing (SIP) allow researchers to track organic compound transformations and microbial activity while providing an integrated view of soil biogeochemical processes (Wang et al. 2025). CSIA showed biodegradation drives anilide pesticide loss in leachates, planted soils, and forest soils and that sorption and leaching affect bulk soils (Pérez-Rodríguez et al. 2021).

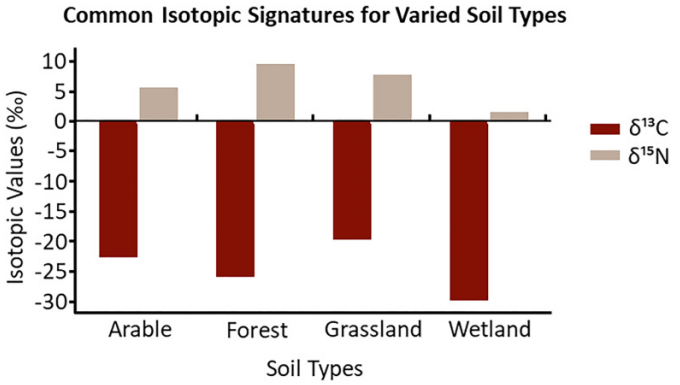
Other new technologies employ laser spectroscopy and high-resolution mass spectrometry (HRMS) to provide highly accurate real-time measurements regardless of the potential remoteness of field settings (Saurer et al. 2023). These approaches improve the resolution of carbon dynamics monitoring studies over time with a level of detail previously unattainable by serving as real-time tracers of carbon and water fluxes. Isotope ratios measured by these tools are guided by environmental factors such as soil moisture and temperature as they influence isotopic fractionation during processes such as respiration and transpiration. Combining these cutting-edge techniques with remote sensing technologies could provide an even greater advantage for studies across larger spatial scales, over extended periods, and those aiding forest management strategies geared towards maximization of carbon sequestration in response to climate change.

Another promising discovery is the integration of stable isotope fractionation models with ecosystem-level nutrient cycling data. Recent studies have reported that isotope fractionation can be used to model carbon fluxes, nitrogen, and water dynamics, and provide a holistic understanding of how forest ecosystems respond to changing environmental conditions (Dai et al. 2023). Isotope ratios in these models reflect the balance between nutrient and water sources and sinks. Here, fractionation effects explain how isotopic values are altered by processes such as microbial transformation. Forest managers can develop more effective strategies for addressing forest resilience amidst climate change by adding isotopic data to other environmental and biological variables.

Despite the continued integration of stable isotopes into forest and soil management strategies, several knowledge gaps remain despite the additional insight they have provided on various topics. One of the largest gaps is in understanding long-term carbon stability in forest soils. The measurement of short-term carbon fluxes has become a fairly popular pursuit of stable isotope studies but deep soil carbon dynamics over extended (decadal, century-long) timescales remained unexplored (Hicks Pries et al. 2023; Koutika 2025). More accurate assessments of deep carbon stability in old-growth forests could uncover essential data for use in more accurate assessments of their role in long-term climate mitigation strategies. These studies use δ^{13}C isotopic ratios to reflect carbon source stability and turnover and show that changes in fractionation signal long-term microbial decomposition or stabilization.

Interactions between isotopic markers and different forest management practices are also not well understood. Stable isotopes are effective in tracking soil carbon dynamics,

Fig. 3. Common isotopic signatures for varied soil types.



but more research on how forest management interventions such as selective logging, thinning, or prescribed burning influence the carbon cycle and soil isotopic signatures is desperately needed. Changes in $\delta^{13}C$ and $\delta^{15}N$ ratios can trace shifts in carbon and nitrogen cycling caused by disturbance and reflect altered microbial activity or plant inputs. Long-term studies in mixed or tropical forests help determine whether remediation methods improve or disrupt carbon storage across different management systems (Raihan 2024).

Another critical area for future research is the role of microclimates in influencing isotopic signatures of carbon and nitrogen in soil (Fig. 3). Recent studies have reported on the influence of macroclimate on carbon cycling, but the effects of microclimates—such as variations in temperature, moisture, and canopy cover—on isotopic signatures in forest soils have received considerably less attention (DeFrenne et al. 2021; Ma et al. 2022). In this example, isotopic ratios reflect microclimatic shifts by capturing changes in fractionation that point to variations in carbon and nutrient cycling. Research focusing on how microclimatic variability influences carbon sequestration at different soil depths may reveal new insights into soil health and carbon stability while providing actionable knowledge for forest restoration and management efforts.

Laser spectroscopy and HRMS are fairly new tools in forest research. Newer tools such as nano-scale secondary ion mass spectrometry (nanoSIMS) show promise for isotopic analysis at the microscopic level. NanoSIMS can trace the movement of isotopes within individual plant cells and provide a highly detailed understanding of how carbon is incorporated into soil through root exudates and microbial activity (Vidal et al. 2018; Wen et al. 2022; Mir et al. 2024). This technique introduces a precise way to trace isotopic incorporation at the cellular level and reveals how microbial metabolism and stress mediate carbon stabilization in soils. NanoSIMS can also provide valuable insight into how forest ecosystems contribute to long-term carbon storage.

Multi-isotope systems studies (MIS) are also promising. Simultaneous measurement of multiple isotopes such as $\delta^{13}C$, $\delta^{15}N$, and $\delta^{18}O$ in soil and plant samples provides researchers with a more comprehensive picture of nutrient cycling and ecosystem productivity. This integrated approach can provide a better understanding of interactions between multiple biogeochemical cycles and how altering one cycle influences carbon sequestration and storage capacity in forest soils (Snyder et al. 2022; Zhao et al. 2023; Tang et al. 2024). These ratios can work synergistically to trace nutrient source, sinks, and cycling while offering deeper insight into ecosystem processes. Developing these methods alongside traditional methods can provide the impetus for the development of more universal and adaptive management strategies.

Conclusion

This synthesis highlights stable isotope analysis as a fundamental tool for understanding soil dynamics and promoting sustainable forest management. From tracing nutrient cycling and carbon sequestration to analyzing microbial processes and pollutant impacts on forest soils, stable isotopes offer multifaceted insights into forest ecosystem health and productivity by serving as tracers of carbon source origin, signatures of physiological and microbial processes, and indicators of soil nutrient sources or sinks. These methods support adaptive management, enable early detection of soil degradation, and enhance resilience in forests under anthropogenic pressure. Isotope analysis has significant potential for ecosystem restoration. Integration of isotopic data with nutrient models, remote sensing, and traditional assessments creates a strong framework for long-term monitoring and improved accuracy in carbon sequestration predictions. For example, ecosystem-level nutrient cycling models could yield a more comprehensive understanding of soil health and how different forest management practices like controlled burns and thinning alter $\delta^{13}C$ and $\delta^{15}N$ ratios. These changes would indicate microbial turnover, litter quality, and nitrogen-use efficiency. Microbial-driven shifts in $\delta^{13}C$ and $\delta^{15}N$ reflect soil respiration and carbon stabilization. Isotopic enrichment patterns after disturbance reveal both short-term ecosystem responses and longer-term recovery processes. Tracers of heavy metals and fallout radionuclides, including $\delta^{206}Pb/\delta^{207}Pb$ and $\delta^{137}Cs$, support source attribution for contamination and erosion to enable precise spatial targeting for remediation and conservation. These isotopic patterns are dynamic and influenced by climate extremes, urbanization, land-use history, and soil texture. Interdisciplinary collaboration will be essential to ensure findings are translatable into balanced economic, ecological, and global ecosystem sustainability.

Advanced techniques such as compound-specific stable isotope analysis (CSIA), laser spectroscopy, NanoSIMS, and MIS expand analytic capabilities and offer greater precision and real-time monitoring of nutrient and carbon fluxes. These tools help forest managers to adapt practices based on collected data. CSIA and NanoSIMS provide distinct isotopic tracers and signatures that reveal underlying biogeochemical processes and environmental influences. They also enable the identification of microbial, root, and litter contributions to SOM and allow visualization of nutrient transformation pathways crucial to understanding stabilization mechanisms. Integrating isotopic tools with genomic selection and ecosystem modeling can refine predictions of climate stressor impacts and improve the scalability of carbon se-

questration models in both temperate and tropical forest systems. Stable isotope analysis advances the understanding of complex biogeochemical processes but also strengthens adaptive approaches aligned with global conservation goals. Future research efforts could prioritize expanding the spatial and temporal resolution of isotopic monitoring while clarifying how disturbance events such as erosion, pollution, or microbial shifts alter isotope ratios across soil layers and forest types. It would also be helpful for the research community to support development of a global soil health database, standardization of isotope measurement protocols, and integration of isotopic tools into real-time monitoring systems. This approach can help forest managers to make informed, data-driven decisions as climate variability and human activities continue to disrupt natural cycles.

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Supplementary material

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Appendix A

Table A1. Each entry lists the study, isotopes used, isotope function (e.g., tracer or signature), the key environmental factor investigated, and the main observed isotopic change.

Study	Isotope(s)	Function	Key environmental factor	Observed isotopic change
Amundson et al. (2003)	$\delta^{15}N$	Tracer/Signature	Global MAT and MAP	$\delta^{15}N$ shifts with N conservation or loss
Angst et al. (2019)	$\delta^{14}C$, $\delta^{15}N$	Signature	SOM stabilization	$\delta^{14}C$ depletion = old carbon; $\delta^{15}N$ = microbial retention
Aranda et al. (2012)	$\delta^{66}Zn$	Tracer	Acid rock drainage	Lighter $\delta^{66}Zn$ mobilized during weathering
Araújo et al. (2024)	–	–	Mine tailings	No isotope used, restoration focus only
Badea et al. (2021)	$\delta^{13}C$, $\delta^{18}O$	Signature	Photosynthesis and evapotranspiration	Both isotopes indicated moisture stress
Caro et al. (2023)	$\delta^{13}C$, $\delta^{15}N$	Tracer	Microbial growth	Isotopic ratios revealed slow assimilation
Charbonnier et al. (2020)	$\delta^{138}Ba$	Tracer	Amazon sediment transport	Biocycling altered $\delta^{138}Ba$ in sediments
Chaschina et al. (2018)	$\delta^{15}N$	Signature	Cu pollution and roots	$\delta^{15}N$ enrichment from Cu-altered cycling
Cherubini et al. (2021)	$\delta^{13}C$, $\delta^{18}O$	Signature	Tree-ring soil productivity	Long-term $\delta^{13}C$, $\delta^{18}O$ reflect site history
Cloquet et al. (2006)	Cd, Pb isotopes	Tracer	Industrial vs. natural Cd/Pb sources	δCd and δPb separated pollution sources
Craig et al. (2022)	$\delta^{13}C$, $\delta^{18}O$	Tracer	Litter quality	$\delta^{13}C$ depletion in CO_2 flux
Dawson and Siegwolf (2007)	$\delta^{13}C$, $\delta^{18}O$	Signature	Long-term monitoring	$\delta^{13}C$ used in root/SOM tracing
Diao and Wu (2024)	$\delta^{13}C$	Tracer	Rainfall events	$\delta^{13}C$ depletion from mixed CO_2 sources
Dulamsuren and Hauck (2021)	$\delta^{13}C$, $\delta^{15}N$	Signature	Drought and N source	$\delta^{13}C$ enriched (drought); $\delta^{15}N$ indicated livestock N
Fajardo et al. (2022)	–	–	Forest degradation	No isotope used; ML thresholds for species loss
Gallarotti et al. (2021)	–	–	N_2O flux in tropics	N gas flux focus; no isotopes listed
Gao et al. (2018)	$\delta^{13}C$	Tracer	PAH source identification	Differentiated biogenic vs. petrogenic sources
Gao et al. (2022)	$\delta^{114}/^{110}Cd$	Tracer	Vertical Cd migration in mining soils	Heavier δCd enriched with depth
Gelly et al. (2019)	Pb isotopes	Signature	Legacy smelter pollution	Pb ratios indicated persistent smelter-derived Pb
Graydon et al. (2009)	199 Hg, 200Hg	Tracer	Plant uptake of Hg	Isotopic evidence of aboveground Hg capture
Greenlon et al. (2022)	$H_2{}^{18}O$	Tracer	Precipitation	Increased ^{18}O in DNA
Herzog et al. (2019)	$\delta^{13}C$, $\delta^{15}N$	Tracer/Signature	Moisture	$\delta^{15}N$ increased with immobilization
Huang et al. (2024)	$\delta^{13}C$	Tracer	Elevated CO_2 + Cd	$\delta^{13}C$ reflected stress response and phytostabilization
Jiang et al. (2015)	^{13}C-DNA SIP	Tracer	Phenanthrene degraders	Identified specific microbes in polluted soil
Jiskra et al. (2019)	Hg isotopes (MDF, MIF)	Signature	Mercury sources	Source-dependent isotopic fingerprints
Kendall et al. (2007)	$\delta^{15}N$, $\delta^{18}O$	Tracer/Signature	Nitrate pollution	$\delta^{15}N$ enriched (manure), $\delta^{18}O$ from atmospheric O_2
Kim et al. (2023)	$\delta^{13}C$, ^{14}C	Tracer	Recent vs. legacy phenol	Dual isotopes distinguished source origin
Klimek et al. (2021)	–	–	Temperature effect	Respiration increased with temperature (no isotope)
Kribek et al. (2018)	$\delta^{65}Cu$	Tracer	Smelter Cu contamination	Isotopic match between soil and plant Cu
Laceby et al. (2015)	$\delta^{13}C$, $\delta^{15}N$,^{137}Cs, $^{210}Pb_{ex}$	Tracer	Erosion provenance	Cs and Pb_{ex} preferred over $\delta^{13}C/\delta^{15}N$ due to reactivity
Liu et al. (2020)	$\delta^{66}Zn$	Tracer/Process	Zn migration (redox)	Isotopic shift by vertical/lateral migration
Liu et al. (2021)	$\delta^{13}C$, $\delta^{2}H$ (CSSI)	Tracer	SOM erosion flux	$\delta^{13}C$ and $\delta^{2}H$ used for tracing SOM source
Liu et al. (2022)	$\delta^{13}C$	Tracer	Successional SOC	$\delta^{13}C$ shifts with succession phase

Table A1. (*concluded*).

Study	Isotope(s)	Function	Key environmental factor	Observed isotopic change
Lyu et al. (2019)	$\delta^{15}N$	Signature	Litter input	$\delta^{15}N$ enrichment
Ma et al. (2021)	$\delta^{13}C$, $\delta^{15}N$	Tracer	Dormant-season N uptake	Tissue $\delta^{15}N$ enriched during winter
Madsen (2006)	^{13}C (SIP)	Tracer	Biodegradation	Tracked labeled contaminants into microbes
Manninen et al. (2022)	$\delta^{13}C$, $\delta^{15}N$	Tracer	NO_x pollution	$\delta^{13}C$ enrichment (water stress), $\delta^{15}N$ from NO_x uptake
McDermot et al. (2020)	$\delta^{15}N$	Signature	Urbanization intensity	$\delta^{15}N$ increased in foliage
Mohan et al. (2021)	–	–	UAV-seeded restoration	No isotopes used
Oakes (2017)	δ13C (CSIA)	Tracer	PAHs, sterols, transformation	$\delta^{13}C$ linked to compound-specific source
Ontman et al. (2023)	δ15N	Tracer	pH and microbial response	$\delta^{15}N$ variation with NH_4^+ vs NO_3^- uptake
Panchal et al. (2022)	δ13C	Tracer	SOC from root exudation	$\delta^{13}C$ tracked root-derived C into SOC
Paul et al. (2021)	$\delta^{60}Ni$	Signature	Biotic Ni cycling	Biotic Ni in upper soils from phytoaccumulation
Rijk and Ekblad (2020)	$\delta^{13}C$, $\delta^{15}N$	Signature	Pb pollution and microbial activity	$\delta^{13}C$ stable; $\delta^{15}N$ enriched; reduced microbial activity
Shestakova et al. (2019)	$\delta^{13}C$	Signature	European tree response	Enrichment indicated drought-prone soils
Ramesh et al. (2024)	$\delta^{15}N$	Signature	Elevation and SOM	$\delta^{15}N$ decreased with higher OM retention
Siqueira et al. (2020)	–	–	Agroforestry SOC	No isotopic application; SOC tracking only
Soba et al. (2021)	$\delta^{13}C$, $\delta^{15}N$	Tracer	Urban Pb, Cd, Cr	$\delta^{14}N$ and $\delta^{13}C$ track traffic pollutant uptake
Souto-Oliveira et al. (2018)	Pb, Zn, Cu isotopes	Signature	Aerosol origin	Distinguished vehicle vs. industrial sources
Uhlig et al. (2017)	^{26}Mg	Tracer	Rock weathering	Mg traced nutrient export and uptake
Veselkin et al. (2019)	$\delta^{13}C$, $\delta^{15}N$	Signature	Cu emissions	$\delta^{15}N$ enrichment; stable $\delta^{13}C$
Wang et al. (2022*b*)	Hg isotopes	Tracer	Hg transport/transformation	Revealed Hg(II) absorption from atmosphere
Wang et al. (2023*a*)	–	–	Oak regeneration modeling	No isotope used
Wasylenki et al. (2014)	$\delta^{114}/^{110}Cd$	Tracer	Adsorption to Mn oxyhydroxide	Lighter δCd preferentially adsorbed
Wei et al. (2024)	$\delta^{15}N$, $\delta^{18}O$	Tracer	Land use/nitrate	$\delta^{15}N/\delta^{18}O$ linked to fertilizer vs. atmospheric sources
Werner et al. (2012)	$\delta^{13}C$, $\delta^{18}O$	Signature	C and water use across scales	$\delta^{13}C/\delta^{18}O$ reflect stomatal regulation
Xiang et al. (2022)	$\delta^{13}C$	Tracer	SOC from mixed plantations	Enrichment reflected plant-derived carbon
Xu et al. (2025)	$\delta^{114}/^{110}Cd$	Tracer	Clay mineral binding	Lighter δCd retained by clays
Yan et al. (2021)	$\delta^{114}/^{110}Cd$	Tracer	Iron (oxyhydr)oxide interaction	Adsorption favored light, substitution heavy δCd
Zhao et al. (2024)	–	–	Particle size and metals	No isotope used, particle distribution focus
Zwetsloot et al. (2020)	$\delta^{13}C$	Tracer	Root metabolites	$\delta^{13}C$ enrichment in respired CO_2

Note: The table highlights how stable isotopes are used to trace sources, processes, and impacts of pollutants, organic matter, and nutrient cycling in various terrestrial environments.