



Harnessing Isotope Analysis for Wood Identification: Techniques, Applications and Future Directions

Clara Manasa P A*, Deepthi Dechamma N.L. and Nandhakumar S
College of Forestry, Ponnampet, University of Agricultural Sciences, VC Farm, Mandya
*Email: claramanasapa@gmail.com

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Abstract

Accurate identification and traceability of timber are essential for forest management, conservation, legal trade and combating illegal logging. Conventional anatomical identification may be limited in processed wood, while DNA-based methods can be affected by degradation. Stable isotope analysis provides a complementary approach by using isotopic signatures incorporated into wood during growth. This review examines the applications, strengths, challenges and prospects of isotope-based wood identification. Stable isotopes of carbon, oxygen, hydrogen, nitrogen and strontium provide information on environmental conditions and support provenance assessment. Isotope ratio mass spectrometry (IRMS), combined with cellulose preparation and isoscape modelling, enables comparison of unknown timber with reference datasets. Applications include timber-origin verification, illegal logging control, Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) enforcement, supply-chain traceability, forensics and archaeological provenance. Limitations include high costs, specialized equipment, limited reference datasets and variable isoscape resolution.

Keywords: Timber provenance, Isotope ratio mass spectrometry, Isoscape, Geographic origin, Timber tracing, Illegal logging

Introduction

Wood identification plays a crucial role in forestry, archaeology and the timber trade. Accurate determination of wood species and geographic origin is essential for sustainable forest management, cultural heritage preservation and combating illegal logging (Wheeler and Baas, 1998). Traditional identification methods, such as anatomical and morphological analyses, often lack precision and reliability. In recent years, isotope analysis has emerged as a robust tool to enhance the accuracy of wood identification (Silva *et al.*, 2025). Isotope analysis involves examining the ratios of stable isotopes in wood samples. These non-radioactive isotopes provide unique environmental signatures, allowing scientists to trace wood origins and growth conditions.

Stable isotope analysis has emerged as a valuable forensic tool for verifying timber origin and combating illegal logging. The isotopic composition of wood reflects local environmental conditions, with $\delta D/\delta^2H$ and $\delta^{18}O$ ratios linked to the isotopic composition of

precipitation and soil water at specific locations, enabling geographic tracing (Boner *et al.*, 2007). Strontium isotope ratios ($^{87}Sr/^{86}Sr$) correlate with the geo-lithological composition of growing areas, making them particularly effective origin markers (Aguzzoni *et al.*, 2025). When combined with multi-element analysis and chemometric approaches, these isotopic fingerprints can discriminate timber from different geographic origins, achieving cross-validation rates of up to 86.6% (Rees, 2015). Studies in tropical regions, such as Gabon, have demonstrated relationships between climatic and geological variables and stable isotope ratios, supporting origin classification across forest concessions (Watkinson *et al.*, 2022). These methods support compliance with regulations such as the EU Timber Regulation and the Lacey Act.

Wood identification and provenance tracing have advanced considerably through anatomical, molecular and chemical approaches (Yin *et al.*, 2020). Stable isotope analysis represents a particularly promising forensic tool, with D/H and O/O ratios reflecting characteristic isotopic compositions of local

precipitation and soil water, enabling geographic origin determination across regions such as Northern Europe and Southeast Asia (Boner *et al.*, 2007). Building on this foundation, multielement fingerprinting combined with strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) has demonstrated strong potential for timber traceability at regional scales. Studies in the Eastern Alps showed that multielement profiles reliably distinguished Norway spruce, European larch and Swiss stone pine, while $^{87}\text{Sr}/^{86}\text{Sr}$ ratios correlated with geo-lithological composition, enabling accurate geographic classification even among stands sharing the same bedrock type (Aguzzoni *et al.*, 2024; Aguzzoni *et al.*, 2025). Together, these integrated chemical and isotopic approaches offer robust forensic tools to combat illegal timber trade and support sustainable forestry certification.

Why Wood Identification Matters

Wood identification plays a crucial role in enforcing international conservation policies, verifying timber supply chain integrity and combating illegal logging (Koch *et al.*, 2015; Van Brusselen *et al.*, 2023). Traditional wood anatomy techniques using light microscopy can typically identify wood to the genus level, but species-level identification is often required for CITES legislation (Gasson, 2011). Recent advancements in artificial intelligence, biotechnology and chemical analysis show promise in improving wood identification accuracy (Yin *et al.*, 2020). High-value wood species like *Dalbergia* (rosewood) and sandalwood face threats from illegal logging and unsustainable harvesting (Innes, 2010; Bunney *et al.*, 2023). Despite regulations, enforcement remains challenging due to difficulties in verifying timber origin and species identification (Gasson *et al.*, 2010). To address these issues, researchers are developing various scientific tools for timber tracking and origin verification.

Wood identification traditionally relies on anatomical analysis of macro- and microscopic features (Koch *et al.*, 2015). However, recent advances in molecular techniques have enhanced species-level identification and origin determination. DNA barcoding has emerged as a promising tool for timber identification, contributing to trade monitoring and forest conservation (Jiao *et al.*, 2020). Molecular marker methods can be applied at various levels, from species identification to individual log tracking, offering quick, high-volume processing with statistical certainty (Lowe and Cross, 2011).

Nonetheless, both anatomical and genetic

approaches present limitations (Yin *et al.*, 2020; Low *et al.*, 2022). Wood anatomy may be altered or obscured in processed products such as veneer, pulp, or charcoal. DNA analysis offers a promising alternative, allowing species identification and origin tracking of timber products (Tsumura *et al.*, 2011). However, DNA can degrade under certain conditions, potentially compromising its effectiveness. In such contexts, stable isotope analysis offers a complementary and often more resilient technique. Unlike methods focused on species-level identification, isotope analysis enables the determination of geographic origin based on the isotopic signatures of hydrogen, oxygen, carbon and nitrogen embedded in the wood's cellulose matrix (Watkinson *et al.*, 2020). These isotopic signatures correlate strongly with local precipitation patterns and climate variables (Keppler *et al.*, 2007; Boner *et al.*, 2007). This approach offers advantages over traditional dendroprovenancing methods, especially when morphological or genetic data are unavailable or degraded.

Principles of Isotope Analysis

All chemical elements exist in different forms called isotopes (Ellam, 2016). Some are unstable and radioactive, like carbon-14, which is used in carbon dating. But others are stable, like carbon-13, oxygen-18 and hydrogen-2 (deuterium). These stable isotopes (Table 1) do not decay and they are found in varying proportions in nature (Xia and Yu, 2019).

When a tree grows, it absorbs elements from its environment—water from rain, nutrients from soil, carbon dioxide from the air. Each of these carries specific isotopic “signatures” that reflect local climate, geography and altitude. These signatures are locked into the wood's cellulose structure, like a chemical fingerprint. By analyzing these fingerprints using isotope ratio mass spectrometry (IRMS), scientists can tell not only what kind of environment the tree grew in, but potentially where in the world it came from (Werner and Brand, 2001; Muccio and Jackson, 2009) (Fig. 1).

Table 1. Major isotopes used in wood identification

Stable isotope	Principal environmental source	Major controlling factors	Information obtained	Application
$\delta^{13}\text{C}$	Atmospheric CO_2	Photosynthesis, water availability	Physiological/environmental conditions	Timber provenance
$\delta^{18}\text{O}$	Precipitation	Rainfall, altitude	Geographic/climatic	Geographic origin

	tion/soil water	temper ature, evapora tion	matic signature	c origin
$\delta^2\text{H}$	Precipita tion/soil water	Rainfall source, climate, evapora tion	Geographic signature	Provenanc e determina tion
$\delta^{15}\text{N}$	Soil nitrogen	Soil process es, vegetati on, nutrien t cycling	Ecological/site information	Origin discrimina tion
$^{87}\text{Sr}/^{86}\text{Sr}$	Geologic al substrat e/soil	Bedroc k and soil geology	Geographical/geological signature	Dendropro venancing

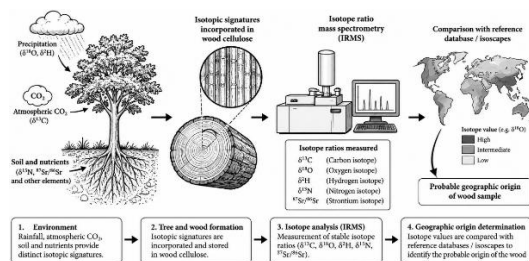


Fig. 1. Principle of isotope-based wood identification

From Forest to Lab: How Isotope Analysis Works

Isotope ratio mass spectrometry (IRMS) is a specialized technique that measures the relative isotopic abundances of elements such as carbon, hydrogen, oxygen and nitrogen to determine the geographic, chemical and biological origins of substances (Muccio and Jackson, 2009). The spatial distribution of these isotope ratios across landscapes forms what is known as an "isoscape," (Fig. 2.) which can be modeled and used to establish spatial connectivity in biogeochemical and ecological systems (Bowen, 2010). To ensure accurate isotopic measurements, wood samples are processed to isolate cellulose, with interlaboratory comparisons demonstrating that standardized cellulose preparation methods yield consistent IRMS results within acceptable precision ranges for carbon, oxygen and hydrogen isotopes (Boettger *et al.*, 2007). Recent technological advances, such as laser ablation IRMS, now enable high-resolution oxygen isotope analysis of cellulose and wood at a spatial resolution of 100 μm , opening new research opportunities in ecology and related fields (Sahlstedt *et al.*, 2025).

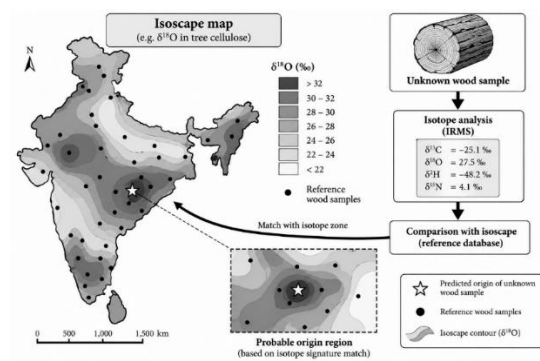


Fig. 2. Illustration of Isoscape concept for geographic origin determination

These data points are plotted on geographic maps to create isoscapes that show how isotope values vary across regions. These signatures can be mapped into isoscapes, which model how isotope values vary spatially. For example, Watkinson *et al.* (2020) developed isoscapes for U.S. oak using climate variables, finding that oxygen and hydrogen isoscapes performed best, with 100% and 94% of test samples falling within two standard deviations of model predictions, respectively. Similarly, Kagawa and Leavitt (2010) demonstrated that carbon isotope time series from tree rings could provenance timber with a precision of 114–304 km. Beyond timber, isoscapes have been applied to human identification, with Ammer *et al.* (2020) successfully predicting regions of origin for undocumented border crossers using oxygen isotope maps of Mexican tap water. Once the isoscapes are developed, unknown wood samples—like those from a seized shipment or a suspicious warehouse—can be tested. The sample's isotopic signature is compared against the reference maps to estimate its geographic origin (Fig. 3.).

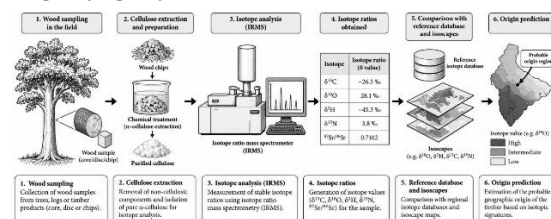


Fig. 3. Workflow of isotope analysis for timber tracing

Real-World Applications

1. Fighting Illegal Logging

Illegal logging is a serious global problem affecting both tropical and non-tropical timber-producing countries. Estimates of illegal timber's share of global trade vary, with some sources citing approximately 15% (Grant and Chen, 2021; Contreras-Hermosilla, 2002), making it one of the world's largest

transnational crimes (Grant and Chen, 2021). Governments, customs agencies and environmental watchdogs are using isotope analysis to verify the origin of wood shipments and catch false declarations. For example, if a shipment is labeled as plantation-grown mahogany from Peru but carries an isotope signature matching trees from a protected forest in Brazil, that's a red flag. Isotope analysis becomes a scientific witness in court, providing hard evidence to prosecute timber fraud. Deklerck (2023) reviewed mass spectrometry approaches including Stable Isotope Ratio Analysis (SIRA) and Direct Analysis in Real Time-Time of Flight Mass Spectrometry (DART-TOFMS), highlighting key scientific challenges that must be resolved before these techniques can be routinely applied at scale. Most recently, Sarkar *et al.* (2025) developed a machine learning pipeline integrating isotope values with atmospheric variables to determine timber harvest locations, outperforming existing models and being actively deployed by European enforcement agencies to identify harvest location misrepresentation.

2. Supporting CITES and Trade Regulations

Enforcing CITES regulations on endangered timber species requires multiple analytical approaches beyond traditional visual inspection. Wood anatomy using light microscopy can typically identify samples only to genus level, which is insufficient when species-level identification is required under CITES for species like Brazilian Rosewood and Ramin (Gasson, 2011). To address this limitation, chemical methods such DART-TOFMS have been developed to rapidly classify protected *Dalbergia* species and support CITES enforcement (Lancaster and Espinoza, 2012). Stable isotope ratio and multi-element analyses offer another complementary approach, achieving 86.60% cross-validation accuracy in discriminating timber origins across African countries (Rees, 2015). These scientific tools are increasingly important as CITES listings expand; following the 19th Conference of the Parties in 2022, 53 wood species or higher taxa are now listed under CITES (Weerth, 2024), making robust identification methods essential for law enforcement officers worldwide.

3. Ensuring Supply Chain Transparency

Supply chain transparency is increasingly critical for sustainability, with companies leveraging tools like supply chain mapping, traceability and third-party certification to manage environmental impacts (Kashmanian, 2017). In forestry, the Forest Stewardship Council (FSC) plays a central role, though its

certification processes rely on trusted third parties and extensive record-keeping, leaving vulnerabilities to bribery and fraudulent inventory practices (Munoz *et al.*, 2021). Comparing FSC and Marine Stewardship Council approaches reveals that transparency in nonstate certification programs varies significantly, affecting their accountability and legitimacy (Auld and Gulbrandsen, 2010). Isotope analysis adds a new layer of accountability by allowing third-party verification of timber origin. Companies can use it to back their sustainability claims and assure consumers that their purchases are forest-friendly.

4. Archeology and Historical Studies

Isotope analysis and chemical methods have become essential tools in archaeology, helping researchers trace ancient trade routes and understand how materials were transported across civilizations (Table 2). Radiogenic strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis has been widely applied to evaluate models of migration, trade and exchange, as well as to establish the provenance of artifacts, building materials and foodstuffs (Slovak and Paytan, 2011). More broadly, chemistry has become a key component of archaeological research, with trace elements used to determine the origins of artifacts and radiocarbon dating employed to estimate their age (Arnaud, 2006).

Table 2. Applications of isotope analysis

Applicati on	Problem addressed	Isotope/analy tical approach	Potential contributi on
Illegal logging	Misrepresent ation of timber origin	Stable isotope analysis + isoscapes	Geographic origin verification
CITES enforcem ent	Identification and origin verification of protected timber	Stable isotopes + complementar y methods	Regulatory support
Supply- chain tracing	Verification of timber claims	Isotope fingerprinting	Independe nt origin verification
Archaeol ogy	Provenance of historical wood/materi als	Stable/radioge nic isotopes	Reconstruc tion of trade and movement
Timber forensics	Unknown/sei zed timber	Multi-isotope analysis	Evidence for origin assessment

Strengths of the Method

One of isotope analysis's main strengths is its resilience to wood processing. Unlike DNA, which can degrade when wood is exposed to heat, chemicals, or aging, stable isotope ratios remain largely intact. This means even plywood, veneer and furniture can potentially be analyzed. Additionally, this approach is valuable

for combating illegal logging, as paper-based traceability systems remain vulnerable to fraud (Truszkowski *et al.*, 2023). Advances in mass spectrometry have broadened the applicability of stable isotope analyses across multiple elements and disciplines (Minami, 2019). Recent methodological developments have improved isoscape prediction using Gaussian processes and machine learning, enabling continuous geographic origin estimation rather than binary classification, with harvest locations determined within 520 km of the true origin (Truszkowski *et al.*, 2025). Incorporating species distribution data further improves accuracy by up to 36% and active learning tools can optimize future reference sample collection (Truszkowski *et al.*, 2023).

Challenges of the Method

Isotope-based timber tracing shows promise but faces significant challenges. Developing high-resolution isoscapes requires extensive sampling and reference data, which remain scarce in many tropical regions. A pantropical database of 712 trees across 20 countries yielded oxygen isoscapes with limited spatial precision, correctly assigning origin in only 59–79% of cases (Vlam *et al.*, 2025).

Another challenge is the cost and complexity of the required equipment. Mass spectrometers are expensive and require specialized technicians. In Africa, the shortage of MS instruments severely limits Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) monitoring, resulting in underreported environmental and public health data (Aborode *et al.*, 2025). Similarly, in low- and middle-income countries, MS represents a high-cost technology that is often inaccessible to regulatory agencies combating falsified and substandard drugs, necessitating the exploration of more feasible alternatives (Kovacs *et al.*, 2014).

Lastly, while isotope analysis can tell us where a tree might have grown, it cannot identify species on its own. That is why combining it with anatomical or genetic techniques often yields the best results. D'Andrea *et al.* (2023) demonstrated that combining tree-ring width, wood anatomy and strontium isotope ratios significantly improved dendroprovenancing of oak trees at local scales, where individual methods failed to distinguish all sites. Similarly, (Boeschoten *et al.*, 2025) showed that integrating genetics, stable isotopes and elemental concentrations achieved 94% accuracy in identifying Central African timber origins within 100 km, far surpassing individual methods (50–80%). For species identification, (Kim and Kim, 2023) found that genetic

barcoding using *ycf1b*, *rbcL* and *trnH-psbA* effectively complemented anatomical identification for *Pinus* species that were otherwise difficult to distinguish anatomically. A broader review by (Low *et al.*, 2022) confirmed that while anatomical reference data exist for 100% of priority timber taxa, geographic origin data remain limited, underscoring the need for combined methodological approaches to combat illegal logging effectively.

Future Directions: Expanding the Toolbox

The future of isotope analysis in wood science is bright, driven by both technological innovation and growing demand for traceable forest products.

1. **Portable Isotope Analyzers:** Miniaturized, field-ready isotope devices are on the horizon. These could allow customs officers to test wood on the spot at ports or markets, speeding up enforcement.
2. **Improved Isoscape Mapping:** As more reference data are collected, maps will become more detailed and precise, allowing for better geographic resolution, even at the sub-national level.
3. **Blockchain Integration:** There's potential to combine isotope verification with blockchain-based supply chain tracking, creating a tamper-proof digital record of each timber product's origin and journey.
4. **Citizen Science and Community Involvement:** Engaging local communities in sample collection can help build broader reference datasets while also raising awareness about forest conservation.

Conclusion: A Tool for Justice and Sustainability

Stable isotope analysis is not just an academic exercise—it is a practical, science-based tool for justice. It empowers governments to uphold laws, supports companies striving for transparency and gives consumers peace of mind. As deforestation accelerates and the demand for wood continues to rise, the ability to trace timber back to its source has never been more urgent. In the coming years, as isotope techniques become more accessible, collaborative and integrated, they will play a critical role in the global effort to combat illegal logging and promote sustainable forestry. The story of a piece of wood—where it came from, how it was harvested and whether it was traded legally—can be unlocked, one isotope at a time.

Conflict of interest

The authors declare no competing or conflict of interest.

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