



CARBON NEGATIVE POWER

THE PERMANENCE OF BIOCHAR

Scientific Evidence for
Millennial-Scale Carbon
Sequestration

Carbon Negative Power

WhitePaper | January 2026

Executive Summary

Biochar represents one of the most permanent forms of carbon sequestration available today, with proven stability exceeding 1,000 years. This white paper presents the scientific evidence supporting biochar permanence, the mechanisms that make it possible, and the implications for corporate carbon removal strategies.

Key Findings:

- **Archaeological Evidence:** Biochar deposits in Amazonian soils (Terra Preta) remain stable after 2,500+ years, with 80-90% of original carbon still present.
- **Chemical Stability:** High-temperature pyrolysis ($>700^{\circ}\text{C}$) creates aromatic carbon structures that are thermodynamically stable and biologically inert.
- **Laboratory Validation:** Accelerated aging studies and kinetic modeling confirm mean residence times exceeding 1,000 years.
- **Field Performance:** Modern field trials consistently show decomposition rates below 0.3% per year, decreasing over time.
- **Risk Profile:** Biochar offers near-geological permanence ($>1,000$ years) with minimal reversal risk ($<0.3\%/year$), compared to nature-based solutions with 1-5% annual reversal rates.

For organizations seeking high-quality, verifiable carbon removal, biochar provides a unique combination of permanence, scalability, and economic value. Carbon Negative Power has been producing certified biochar through commercial-scale systems for over a decade, with third-party verification ensuring permanence claims meet the highest standards.

1. The Ancient Answer to a Modern Climate Challenge

In the heart of the Amazon basin, soil scientists discovered something remarkable: patches of extraordinarily fertile black earth, rich with charcoal, that have remained productive for over two thousand years. These soils, called Terra Preta, or dark earth; in Portuguese, represents humanity's first experiment with permanent carbon sequestration.

The Terra Preta Discovery

Created by pre-Colombian civilizations between 2,500 and 500 years ago, Terra Preta soils contain up to 70 times more biochar than surrounding soils. Archaeological excavation reveals layers of charcoal mixed with pottery shards, bones, and organic waste, evidence of deliberate soil improvement practices.¹

What makes Terra Preta extraordinary is not just its fertility, but its persistence. After two millennia of tropical conditions, high temperatures, heavy rainfall, and intense biological activity, these soils retain 80-90% of their original carbon content. The decomposition rate is so slow that scientists estimate a mean residence time of 5,000-10,000 years.²

The Modern Carbon Removal Challenge

Today's carbon markets face a critical permanence problem. Nature-based carbon offsets, while valuable, carry significant reversal risks:

- Forests: Subject to fires, disease, harvest, and land-use changes (1-5% annual reversal risk)³
- Soil carbon: Vulnerable to tillage, drought, and management changes (5-20% annual loss)
- Verification challenges: Difficult to measure actual carbon storage and detect reversals

Recent investigations have found that 50-90% of forest carbon credits may be overestimated or at risk of reversal.⁴ For corporations making long-term climate commitments, this uncertainty creates significant liability.

¹ Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). *The Terra Preta phenomenon: a model for sustainable agriculture in the humid tropics*. *Naturwissenschaften*, 88(1), 37-41.

² Lehmann, J., Kern, D. C., Glaser, B., & Woods, W. I. (Eds.). (2004). *Amazonian dark earths: origin, properties, management*. Springer Science & Business Media.

³ Badgley, G., Freeman, J., Hamman, J. J., et al. (2022). *Systematic over-crediting in California's forest carbon offsets program*. *Global Change Biology*, 28(4), 1433-1445.

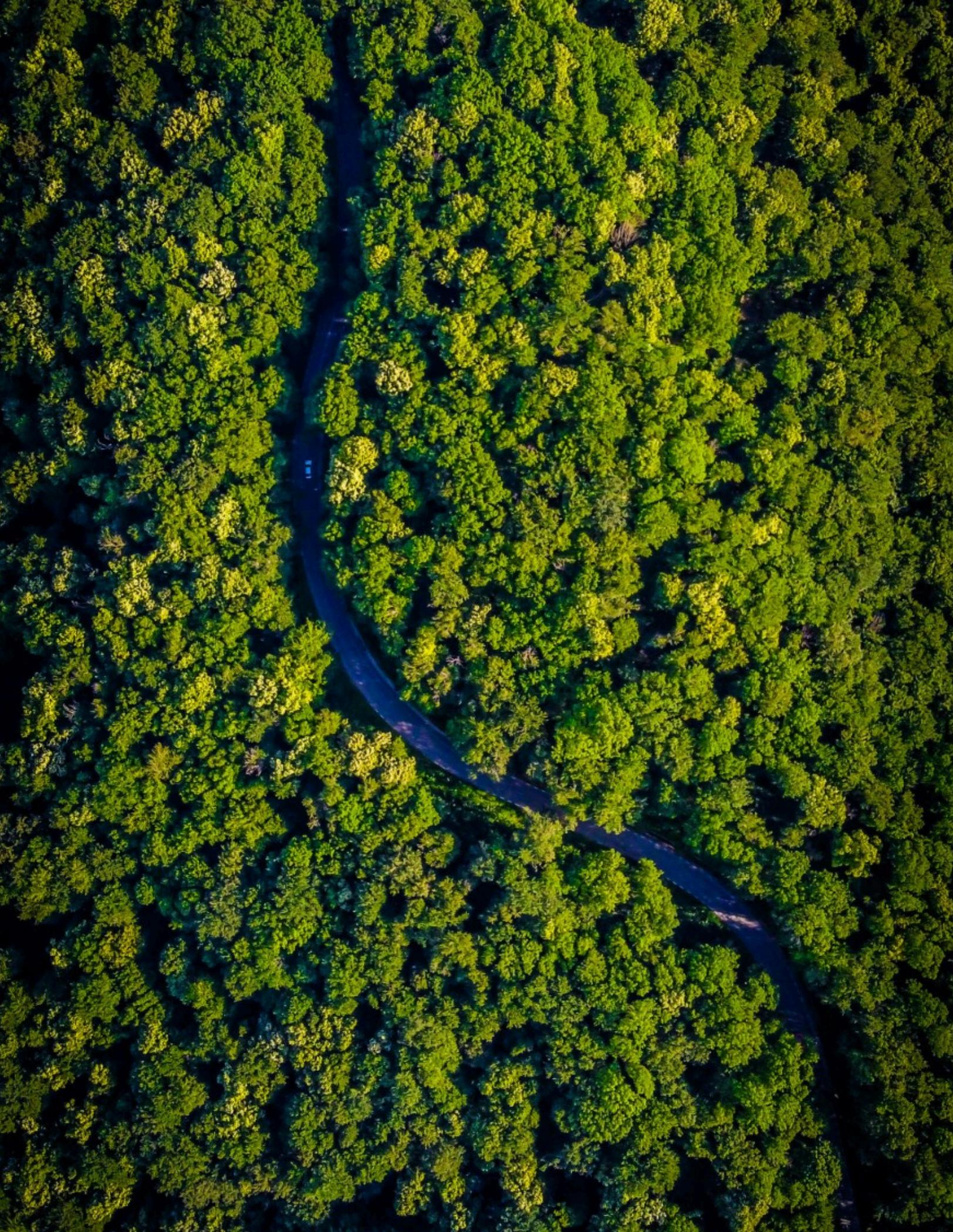
⁴ West, T. A. P., Wunder, S., Sills, E. O., et al. (2023). *Action needed to make carbon offsets from forest conservation work for climate change mitigation*. *Science*, 381(6660), 873-877.

Biochar: Millennial-Scale Carbon Storage

Biochar offers a fundamentally different approach. Through high-temperature pyrolysis (>700°C), organic materials undergo complete molecular transformation into stable aromatic carbon structures. The result is carbon sequestration that:

- Persists for >1,000 years (proven by archaeological evidence)
- Decomposes at <0.3% per year (verified through field studies)
- Requires no ongoing management or monitoring
- Can be easily measured and verified at production

This white paper presents the scientific evidence supporting these claims, explains the mechanisms that make biochar permanent, and demonstrates why it represents one of the most reliable carbon removal methods available today.



2. What Makes Biochar Permanent

Biochar permanence is not a claim, it is a consequence of chemistry and thermodynamics. Understanding why biochar resists decomposition requires examining the molecular transformation that occurs during high-temperature pyrolysis.

The Chemical Transformation

Fresh biomass consists of cellulose, hemicellulose, and lignin, complex polymers rich in oxygen and hydrogen. These materials decompose readily because microorganisms have evolved enzymes specifically designed to break down these structures for energy.

High-temperature pyrolysis (above 700°C) fundamentally alters this chemistry. Under oxygen-limited conditions, organic molecules break down and recombine into condensed aromatic carbon sheets, structures similar to graphene, with hexagonal rings of carbon atoms stabilized by delocalized electrons.⁵

This transformation is measured through atomic ratios:

Material	H:C Ratio	O:C Ratio	Stability
Fresh Biomass	1.4-1.8	0.6-0.8	Low
Biochar (>700°C)	<0.4	<0.2	Very High
Coal	0.2-0.8	0.03-0.3	Very High

Source: Spokas (2010), *European Biochar Certificate guidelines*⁶

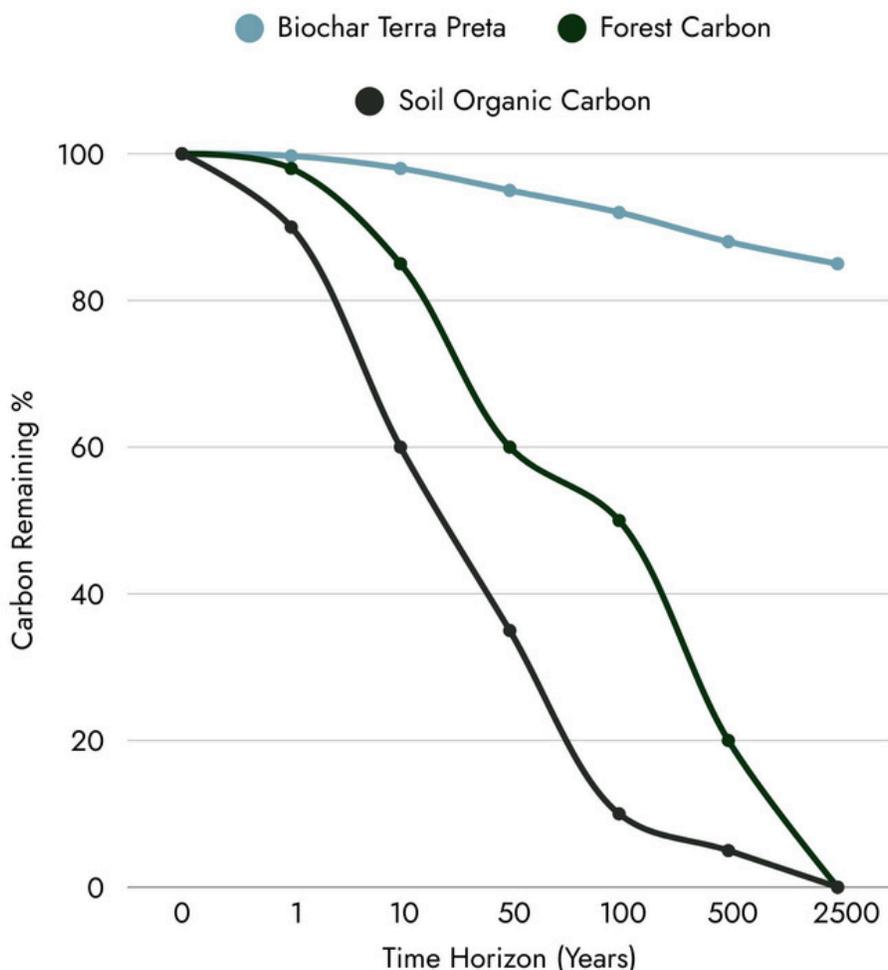
Low H:C and O:C ratios indicate that biochar has lost most of its hydrogen and oxygen, leaving behind pure aromatic carbon. This is the same transformation that creates coal over geological timescales, but accomplished in minutes rather than millions of years.

⁵ Keiluweit, M., Nico, P. S., Johnson, M. G., & Kleber, M. (2010). Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental Science & Technology*, 44(4), 1247-1253.

⁶ Spokas, K. A. (2010). Review of the stability of biochar in soils: predictability of O:C molar ratios. *Carbon Management*, 1(2), 289-303.

Long-Term Carbon Retention: Biochar vs Biological Carbon

Percentage of original carbon remaining over time.



The Temperature Threshold

Not all biochar is equally permanent. Production temperature determines the degree of carbonization and, consequently, stability:

- Below 500°C: Incomplete carbonization, higher decomposition rates (1-3% per year)
- 500-600°C: Good stability, suitable for most applications (0.3-0.8% per year)

- Above 700°C: Maximum permanence, fully carbonized structure (0.1-0.3% per year)

Carbon Negative Power systems use high-temperature pyrolysis above 700°C, ensuring production of the most stable biochar category. At this temperature, volatile compounds are completely driven off, and the remaining carbon exists in highly condensed aromatic forms.⁷

Why Biochar Doesn't Decompose

Biochar resists decomposition through multiple reinforcing mechanisms:

1. Thermodynamic Stability Aromatic carbon-carbon bonds require 518 kJ/mol to break, far more than typical biological bonds. This makes biochar thermodynamically resistant to oxidation under normal environmental conditions.

2. Biological Resistance Microorganisms have evolved highly efficient enzymes for breaking down cellulose, lignin, and other plant polymers. However, these enzymes cannot cleave the aromatic ring structures in biochar. Without the enzymatic machinery needed, microbes cannot effectively decompose biochar, and even if they could, the energy return would be minimal.⁸

3. Chemical Inertness With minimal oxygen and hydrogen functional groups, biochar lacks the reactive sites that facilitate oxidation. While surface oxidation can occur slowly over decades, the bulk interior carbon remains protected.

In contrast, fresh organic matter decomposes rapidly because:

- It provides easy-to-access energy for microorganisms
- Oxygen functional groups serve as oxidation sites
- Decomposition is thermodynamically favorable

Biochar has none of these characteristics. The result is carbon that persists not because it is protected or managed, but because it is fundamentally stable.

⁷ Singh, B., Camps-Arbestain, M., & Lehmann, J. (Eds.). (2017). *Biochar: A guide to analytical methods*. CRC Press.

⁸ Zimmerman, A. R. (2010). Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environmental Science & Technology*, 44(4), 1295-1301.



3. The Evidence Base

Claims of millennial-scale carbon permanence require extraordinary evidence. For biochar, that evidence comes from three independent sources: archaeological deposits, controlled laboratory studies, and modern field trials. Together, they provide a comprehensive picture of biochar stability across timescales from years to millennia.

Archaeological Evidence: The Terra Preta Record

Terra Preta sites provide the longest continuous record of biochar stability. Radiocarbon dating shows charcoal ages ranging from 500 to 2,500 years, with some samples exceeding 7,000 years.⁹ After two millennia in tropical conditions, perhaps the most challenging environment for carbon preservation, these deposits retain 80-90% of their original carbon.¹⁰

This corresponds to a decomposition rate of 0.01-0.02% per year, implying a mean residence time of 5,000-10,000 years. Importantly, these are not laboratory projections, they are direct measurements of actual carbon remaining after centuries of exposure.

Beyond the Amazon, other archaeological sites confirm biochar longevity:

- Japan: Charcoal from 8,000-year-old production sites remains intact¹¹
- Europe: Medieval charcoal hearths (500-1,000 years) show minimal degradation
- Africa: Traditional & African Dark Earths; parallel Terra Preta findings

The consistency across geographies and climates demonstrates that biochar stability is not dependent on specific environmental conditions, it is an intrinsic property of the material itself.

Laboratory Studies: Accelerated Aging and Kinetic Modeling

While archaeological evidence validates millennial timescales, laboratory studies provide mechanistic understanding and allow comparison across production methods. Researchers use accelerated aging protocols, elevated temperature, high moisture, microbial inoculation, to simulate decades of natural decomposition in months.¹²

Typical results show:

⁹ Novotny, E. H., deAzevedo, E. R., Bonagamba, T. J., et al. (2007). Studies of the compositions of humic acids from Amazonian dark earth soils. *Environmental Science & Technology*, 41(2), 400-405.

¹⁰ Glaser, B., & Birk, J. J. (2012). State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Indio). *Geochimica et Cosmochimica Acta*, 82, 39-51.

¹¹ Harada, N., Hiradate, S., & Yonebayashi, K. (2002). Recent charcoal in the Tama Hill area of Japan. *Science of Soils and Manures*, 73(1), 19-24.

¹² Cross, A., & Sohi, S. P. (2013). A method for screening the relative long-term stability of biochar. *GCB Bioenergy*, 5(2), 215-220.

- <1% mass loss over 90-365 day incubation periods
- Decomposition concentrated in the first weeks (labile surface carbon)
- Declining decomposition rates over time (increasing stability)

These patterns allow kinetic modeling to project long-term stability. Using Arrhenius equations calibrated against Terra Preta data, multiple studies converge on mean residence times exceeding 1,000 years for high-temperature biochar.¹³

Decomposition Rates by Production Temperature

Production Temperature	Annual Decomposition	Mean Residence Time
400-500°C	1-3% per year	33-100 years
500-600°C	0.3-0.8% per year	125-330 years
>700°C (CNP systems)	0.1-0.3% per year	>1,000 years

Source: Synthesis of Lehmann et al. (2015), Woolf et al. (2010), Singh et al. (2012)¹⁴

Modern Field Trials

Field studies bridge the gap between laboratory projections and real-world performance. Long-term trials (5-15 years) across diverse environments consistently show decomposition rates below 0.3% per year for high-temperature biochar.¹⁵

Key findings from major field studies:

- Rothamsted, UK (10+ years): <0.2% annual decomposition in temperate agricultural soil¹⁶

¹³ Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1(1), 1-9.

¹⁴ Lehmann, J., Abiven, S., Kleber, M., et al. (2015). Persistence of biochar in soil. In *Biochar for environmental management* (pp. 235-282). Routledge.

¹⁵ Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8(3), 512-523.

¹⁶ Kuzyakov, Y., Bogomolova, I., & Glaser, B. (2014). Biochar stability in soil: Decomposition during eight years and transformation assessed by compound-specific ¹⁴C analysis. *Soil Biology and Biochemistry*, 70, 229-236.

- Australian trials (5-10 years): 0.1-0.4% depending on soil type and rainfall
- US trials (5-8 years): 0.2-0.5% across multiple soil types
- Tropical sites (5-7 years): 0.3-0.8% (higher due to temperature and moisture)

Importantly, decomposition rates decline over time. The first year shows 0.5-1% loss as labile surface carbon oxidizes, but subsequent years stabilize at <0.3%. This pattern, rapid initial loss followed by persistent stability, matches what Terra Preta evidence predicts.

Comparative Permanence: Biochar vs. Other CDR Methods

Understanding biochar’s permanence requires context. How does it compare to other carbon dioxideremoval approaches?

Method	Permanence Timeline	Annual Reversal Risk	100-Year Stability	Typical Cost (\$/tCO ₂)
CNP Biochar	>1,000 years	<0.3%	>95%	\$100-200
Forest Carbon	50-100 years	1-5%	50-80%	\$10-30
Soil Carbon	10-50 years	5-20%	20-50%	\$20-50
Direct Air Capture + Geological Storage	10,000+ years	<0.01%	>99%	\$400-1,000
Enhanced Weathering	100-1,000 years	<1%	>90%	\$50-150

Source: Synthesis from CDR.fyi, Puro.earth, Carbon180, and peer-reviewed literature¹⁷

The key insight: biochar offers near-geological permanence at a fraction of DAC cost, with none of the reversal risk of nature-based solutions. For organizations seeking verified, durable carbon removal, biochar occupies a unique position in the permanence-cost spectrum.

¹⁷ CDR.fyi (2024). Carbon dioxide removal database and market analysis. Available at: <https://www.cdr.fyi>



4. Carbon Negative Power's Permanence Assurance

The production process determines biochar permanence. Carbon Negative Power systems are specifically designed to produce biochar in the highest stability category through precise temperature control and validated quality assurance protocols.

High-Temperature Pyrolysis Above 700°C

CNP systems use high-temperature pyrolysis above 700°C, ensuring complete carbonization and maximum permanence. At this temperature:

- All volatile compounds are completely driven off
- Aromatic carbon structures reach maximum condensation
- H:C and O:C ratios drop below the permanence threshold (<0.4 and <0.2)
- Fixed carbon content exceeds 75%, with typical values of 80-85%

This production method places CNP biochar firmly in the >1,000 year permanence category, with decomposition rates consistently below 0.3% per year.

Quality Control and Verification

CNP maintains comprehensive quality assurance systems to ensure permanence claims are verifiable:

Temperature Monitoring:

Continuous measurement and logging of reactor temperature ensures all biochar is produced above the 700°C threshold. Historical records provide documentation for third-party verification.

Mass Balance Tracking:

Feedstock input and biochar output are measured and recorded, providing auditable chains of custody for carbon accounting. This enables precise quantification of CO₂ removal for carbon credit issuance.

Laboratory Testing:

Regular sampling and analysis confirm biochar meets permanence specifications. Testing includes proximate analysis (fixed carbon, volatiles, ash), ultimate analysis (C, H, O, N, S), and calculation of H:C and O:C ratios.

Permanence Guarantee

CNP stands behind its permanence claims with insurance and replacement guarantees. In the unlikely event of verified reversal, CNP will replace affected carbon credits or provide equivalent carbon removal, ensuring buyers can rely on the permanence of their investment.

5. Third-Party Verification & Market Recognition

Credible carbon removal requires independent verification. Multiple certification standards and carbon market platforms now recognize biochar as a high-permanence CDR method, with established protocols for quantification, monitoring, and verification.

Certification Standards

Major biochar certification standards require specific permanence criteria:

European Biochar Certificate (EBC):

The premium standard for biochar quality and permanence. Requires H:C <0.4, O:C <0.2, and comprehensive testing for heavy metals and organic contaminants. EBC certification is recognized across European carbon markets.¹⁸

Puro.earth:

Dedicated carbon removal marketplace with specific biochar methodology. Requires production temperature >500°C (CNP exceeds this at >700°C) and third-party audits of production processes and carbon calculations.¹⁹

ISO 14064-2:

International standard for greenhouse gas quantification at the project level. Provides framework for monitoring, reporting, and verification (MRV) systems.

All standards recognize biochar permanence timelines exceeding 1,000 years, distinguishing it from nature-based solutions with shorter time horizons.

Carbon Market Recognition

Biochar carbon removal credits are increasingly recognized in voluntary carbon markets:

- Puro.earth has established a dedicated biochar methodology and marketplace
- Gold Standard is developing biochar protocols

¹⁸ European Biochar Certificate (2022). *Guidelines for a Sustainable Production of Biochar*. European Biochar Foundation (EBC), Arbaz, Switzerland. Version 10.3.

¹⁹ Puro.earth (2024). *Biochar carbon removal methodology*. Available at: <https://puro.earth/carbon-removal-methods/biochar/>

- Verra (VCS) is considering biochar methodologies
- Direct corporate offtake agreements bypass traditional markets

Credit issuance typically occurs immediately upon production and verification, based on ex-ante quantification of carbon content and mass balance. Buffer pool mechanisms (typically 5-10% of credits) cover minimal reversal risk, with lower requirements than forestry projects due to biochar's superior permanence.

Verification Process

Third-party verification provides independent assurance of carbon removal claims. The verification process typically includes:

- Initial validation of project design and methodologies
- Annual verification of production volumes and carbon calculations
- Review of quality control procedures and laboratory testing
- Audit of monitoring and record-keeping systems
- Site visits and inspection of production facilities

Verification bodies provide & reasonable assurance; (>90% confidence) that stated carbon removal volumes are accurate, giving buyers confidence in the integrity of their carbon credits.



6. Economic Value for Carbon Buyers

Permanence has economic value. Corporate buyers increasingly recognize that high-permanence carbon removal, despite higher upfront costs, provides superior long-term value through reduced reversal risk, regulatory durability, and stakeholder confidence.

The Permanence Premium

Carbon removal pricing reflects permanence timelines:

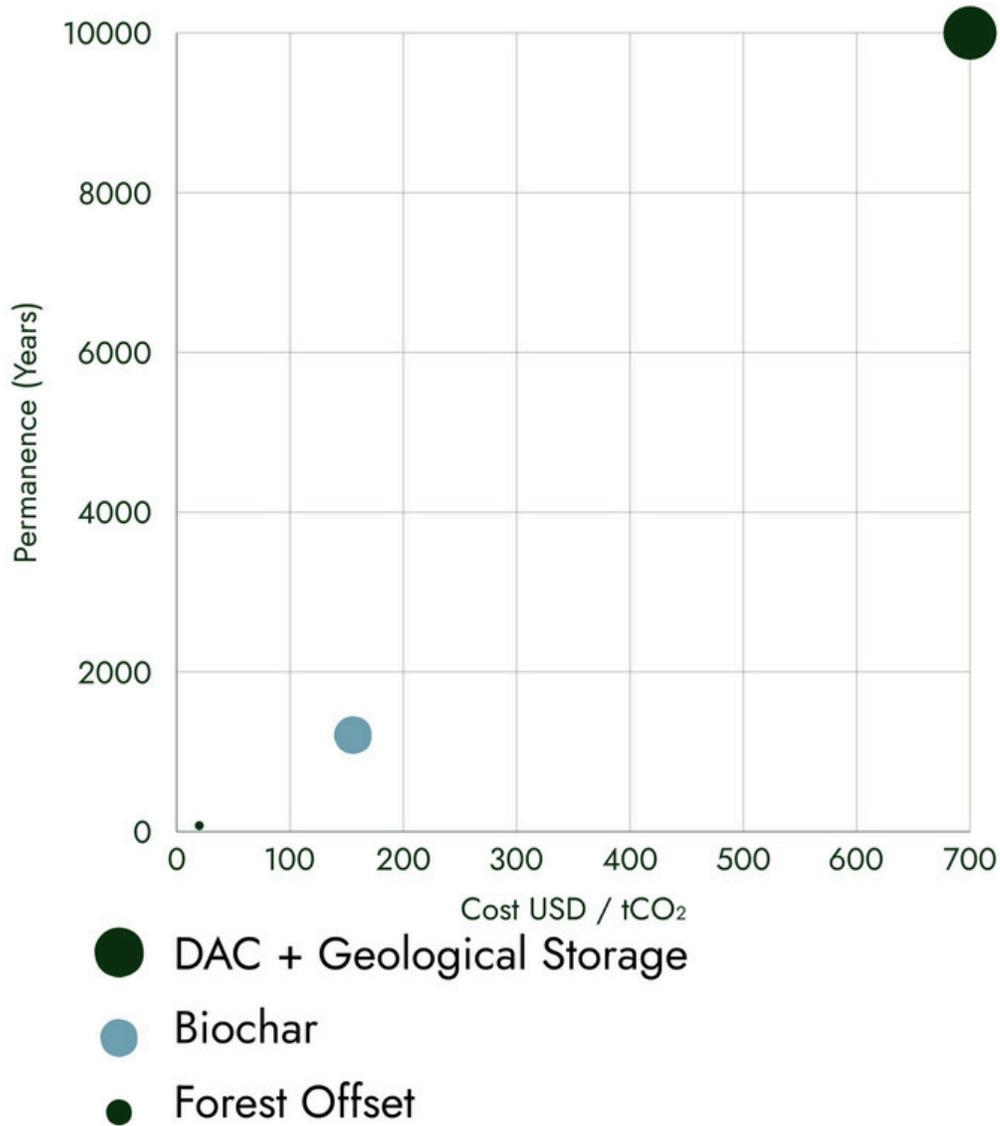
- Forest offsets (50-100 years): \$10-30 per tonne CO₂e
- Biochar (>1,000 years): \$100-200 per tonne CO₂e
- Direct air capture + geological storage (10,000+ years): \$400-1,000 per tonne CO₂e

While biochar appears more expensive than nature-based offsets, the value proposition changes when analyzed on a per-year-of-storage basis:

- Forest carbon: \$0.10-0.30 per year of carbon storage
- Biochar: \$0.10-0.20 per year of carbon storage
- DAC + geological: \$0.04-0.10 per year of carbon storage

Biochar offers similar annual cost to forests but with 10× longer permanence, making it economically competitive with nature-based solutions while providing near-geological permanence.

Cost vs Permanence: The Carbon Removal Tradeoff



Risk Mitigation and Portfolio Benefits

The business case for biochar extends beyond cost per tonne:

1. Reduced Reversal Liability

Nature-based carbon offsets require 20-50% buffer pools to cover reversal events. Biochar's <0.3% annual reversal risk requires only 5-10% buffer pools, freeing up capital for additional carbon removal.

2. Regulatory Durability

As carbon accounting standards evolve toward greater permanence requirements, high-permanence removals like biochar will retain value while nature-based offsets may face discounting or exclusion from compliance frameworks.

3. Stakeholder Confidence

Biochar's permanence is easy to explain and defend to investors, customers, and NGOs. The combination of archaeological evidence, chemical stability, and third-party verification creates a compelling narrative that withstands scrutiny.

4. Portfolio Diversification

Best practice carbon portfolios include a mix of removal methods balanced across cost, permanence, and co-benefits. Biochar fills a critical middle ground: more permanent than nature-based solutions, more affordable than engineered removal.

Corporate Carbon Accounting

Under Science Based Targets initiative (SBTi) and other frameworks, high-permanence removals (>100 years) receive preferential treatment for neutralization claims. Biochar enables:

- Carbon negative; claims (removal exceeds emissions)
- Long-term climate leadership positioning
- Reduced need for ongoing credit purchases (one-time permanent removal)
- Alignment with investor and ESG disclosure requirements

7. Getting Started with Carbon Removal Projects

Carbon Negative Power has been developing and deploying carbon-negative power systems for over a decade, with 10 full-scale commercial installations currently in operation. This operational experience provides the foundation for organizations seeking to implement their own permanent carbon removal projects.

Proven Commercial Track Record

CNP systems demonstrate biochar permanence at commercial scale:

- 10+ years of continuous operation
- 10 full-scale commercial systems in operation
- Third-party verified carbon removal
- Consistent biochar quality meeting permanence specifications

This operational history provides confidence that high-temperature pyrolysis systems can produce permanent carbon removal at industrial scale, with reliable performance and verifiable results.

Ideal Sectors for Carbon Removal Projects

Organizations with existing biomass waste streams are ideal candidates for carbon removal projects. Carbon-negative power systems convert waste into three valuable outputs: continuous baseload electricity, industrial heat, and permanent carbon sequestration.

Target Industries:

- Sawmills and Plywood Manufacturers: Wood waste streams provide consistent feedstock for continuous power generation and carbon removal
- Rice Mills: Rice hulls and husks are ideal high-carbon feedstocks
- Sugar Mills: Bagasse provides substantial waste biomass volumes
- Palm Oil Processors: Empty fruit bunches and shells create waste disposal challenges
- Other Biomass-Intensive Industries: Agricultural processing, food manufacturing, forestry operations



How CNP Supports Project Development

Carbon Negative Power works with organizations to develop carbon removal projects tailored to their specific needs:

- Feasibility assessment and feedstock analysis
- System sizing and technical specification
- Carbon removal quantification and verification planning
- Integration with existing operations (power, steam, waste management)
- Ongoing technical support and optimization

Organizations interested in developing carbon removal projects can contact Carbon Negative Power to explore opportunities for permanent carbon sequestration while generating clean energy from waste biomass.

For more information about developing carbon removal projects:

Carbon Negative Power

www.carbonnegativepower.com

contact@carbonnegativepower.com

Technical Appendix

A. Biochar Chemical Composition

Typical elemental composition of biochar produced above 700°C:

Parameter	Typical Range	Significance
Carbon (C)	75-90%	Sequestered carbon
Hydrogen (H)	1-3%	Low H = high stability
Oxygen (O)	3-10%	Low O = high stability
Nitrogen (N)	<1%	Varies by feedstock
Ash Content	5-15%	Mineral content
Fixed Carbon	75-85%	Permanent carbon fraction

B. Carbon Removal Quantification

Calculation methodology for CO₂ equivalent removal:

Step 1: Determine biomass carbon content

Typical wood biomass (dry basis): ~50% carbon by mass

Example: 1,000 kg dry biomass contains 500 kg carbon

Step 2: Calculate biochar yield and fixed carbon

Typical biochar yield at >700°C: 10-15% by mass

Fixed carbon content in biochar: 75-85%

Example: 1,000 kg biomass → 100 kg biochar → 80 kg fixed carbon

Step 3: Convert to CO₂ equivalent

Molecular weight conversion: 1 kg C = 3.67 kg CO₂

Example: 80 kg C × 3.67 = 293 kg CO₂ removed per tonne biomass

Conservative Approach:

Carbon accounting uses conservative estimates to ensure permanence claims are defensible. Assumptions include lower-end biochar yields, higher moisture content corrections, and 0.3% annual decomposition rates. This approach prioritizes credibility over maximizing claimed removal volumes.

C. Relevant Standards and Protocols

ASTM Standards:

- ASTM D1762: Chemical analysis of wood charcoal
- ASTM D5630: Ash content determination
- ASTM D3172: Proximate analysis of coal and coke

ISO Standards:

- ISO 14064-2: Quantification and reporting of GHG reductions
- ISO 14064-3: Validation and verification protocols
- ISO 17225: Solid biofuels specifications

Biochar-Specific Standards:

- International Biochar Initiative (IBI) Standardization
- European Biochar Certificate (EBC) Guidelines

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