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OPINION

Towards a co-crediting system for carbon and biodiversity

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Societal Impact Statement

Humankind is facing both climate and biodiversity crises. This article proposes the foundations of a scheme that offers tradable credits for combined aboveground and soil carbon and biodiversity. Multidiversity—as estimated based on high-throughput molecular identification of soil meiofauna, fungi, bacteria, protists, plants and other organisms shedding DNA into soil, complemented by acoustic and video analyses of aboveground macrobiota—offers a cost-effective method that captures much of the terrestrial biodiversity. Such a voluntary crediting system would increase the quality of carbon projects and contribute funding for delivering the Kunming-Montreal Global Biodiversity Framework.

Summary

Carbon crediting and land offsets for biodiversity protection have been developed to tackle the challenges of increasing greenhouse gas emissions and the loss of global biodiversity. Unfortunately, these two mechanisms are not optimal when considered separately. Focusing solely on carbon capture—the primary goal of most carbon-focused crediting and offsetting commitments—often results in the establishment of non-native, fast-growing monocultures that negatively affect biodiversity and soil-related ecosystem services. Soil contributes a vast proportion of global biodiversity and contains traces of aboveground organisms. Here, we outline a carbon and biodiversity co-crediting scheme based on the multi-kingdom molecular and carbon analyses of soil samples, along with remote sensing estimation of aboveground carbon as well as video and acoustic analyses-based monitoring of aboveground macroorganisms. Combined, such a co-crediting scheme could help halt biodiversity loss by incentivising industry and governments to account for biodiversity in carbon sequestration projects more rigorously, explicitly and equitably than they currently do. In most cases, this would help prioritise protection before restoration and help promote more socially and environmentally sustainable land stewardship towards a 'nature positive' future.

KEYWORDS

biodiversity banking, biodiversity crediting, carbon crediting, conservation, ecological sustainability, metabarcoding, offsetting, soil biodiversity

1 | INTRODUCTION

The rapid and ubiquitous expansion of agriculture and forestry, in combination with climate change, the direct exploitation of species and other drivers, have collectively resulted in massive losses of native biodiversity worldwide (Bradshaw et al., 2021; IUCN, 2022; Urban, 2015). Today, land use changes constitute the primary threat to species worldwide, with climate change driving key additional risks such as increased physiological stress and loss of suitable habitat or mutualistic partners, putting hundreds of thousands of species at current risk of extinction (Díaz et al., 2019; IPBES, 2019). In an effort to mitigate climate change, there has been tremendous interest by industry, governments and other parts of society in rapidly developing schemes to sequester carbon, either through technological inventions for locking carbon into the substrate or through nature-based solutions, such as the mass planting of trees (Lal, 2008). The problem is that these carbon capture solutions are often deleterious to biodiversity, for example, by promoting rapidly growing tree monocultures instead of natural vegetation (Hua et al., 2022; Lindenmayer et al., 2012). Furthermore, short-rotation bioenergy plantations are poor at mitigating climate change relative to fossil resources and fail to support biodiversity (Camia et al., 2021).

Biodiversity is crucial for ecosystem functioning and for increasing resistance to perturbations, particularly in stressful and increasingly unpredictable environmental conditions (Hong et al., 2022). Positive biodiversity-ecosystem functioning effects are inherent to all domains of life—from microorganisms such as bacteria and fungi to macroorganisms (Yang et al., 2018). Much of biodiversity is built up of rare species (Enquist et al., 2019), which can have a disproportionate effect on ecosystems by performing unique ecosystem services such as generating microclimates, controlling diseases and promoting tight nutrient cycling (Dee et al., 2019). Recent estimates indicate that only around one quarter of the funding sources required for biodiversity conservation are invested in biodiversity globally (Deutz et al., 2020), despite the crucial role of adequate funding to support the ambitious targets recently agreed under the Kunming-Montreal Global Biodiversity Framework (https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222).

Programmes for offsetting carbon and protecting the environment have a relatively short but increasingly influential history. In 1989, the US-based AES Corporation invested two million USD to offset carbon emissions by planting and conserving rainforest in Guatemala. In the early 1990s, the first carbon crediting initiatives were developed to support landowners practising sustainable management of agroecosystems, grasslands and forests that promoted carbon sequestration in aboveground biomass and topsoil (Trexler, 1991). Similarly, biodiversity offsetting programmes have been pursued to counterbalance agriculture-related or industrial land degradation (BBOP, 2012). For example, a payment-for-ecosystem-services programme has been implemented in Costa Rica since 1997 (Pagiola, 2008), and the Chinese Green for Grain programme has been developed to prevent erosion since 1999 (Xu et al., 2006). In the 2000s, offsetting schemes seeking to protect habitats for endangered species were developed in California (Grimm, 2020).

Biodiversity offsetting is related to compensating harm elsewhere and is regarded as the last resort for conservation (BBOP, 2012). By contrast, biodiversity credits are designed to promote conservation of natural biodiversity and restore biodiversity in degraded habitats (Coles, 2023; Porras & Steele, 2020). In other words, biodiversity crediting is a tradable financial support for biodiversity conservation and the restoration of biodiverse natural habitats in wasteland and former agricultural lands, which should be unrelated to offsetting. Although carbon crediting schemes increasingly account for biodiversity effects, no large-scale, operating biodiversity crediting schemes exist (Table 1).

In 2022, methodological frameworks for tradable biodiversity crediting schemes were developed for terrestrial and aquatic biota (Coles, 2023; The Wallacea Trust, 2022). In spite of the current biodiversity crisis, the relatively slow evolution of biodiversity credits is likely because of the multitude of alternative biodiversity metrics (Chao et al., 2014; Lammerant et al., 2021; see also https://geobon.

TABLE 1 Comparison of the proposed carbon-biodiversity co-crediting scheme to existing biodiversity and carbon schemes. The schemes of large companies indicate their general strategies across multiple projects (as of March 2023) unless specifically indicated.

Certification scheme	Carbon and biodiversity assessment	Methodology for biodiversity	Biodiversity measurement units	Comments on biodiversity	Reference
Proposed carbon-biodiversity co-credits	Soil biodiversity, aboveground and soil carbon	Soil DNA metabarcoding (prokaryotes, microeukaryotes, plants and animals)	Multidiversity increase (relative to reference) /ha over 5 years; carbon: 1 t CO_2-eq	Established sampling and analytical protocols	This study
The Wallacea Trust biodiversity credits	Biodiversity only (incl. ecosystem services), co-crediting under development[a]	Plant relevés, camera/audio recordings, remote sensing, ecosystem services and invertebrate metabarcoding	1% net biodiversity increase or avoided loss/ha (relative to reference) over 5 years	No available protocols, expensive monitoring, microbiome not considered	https://wallaceatrust.org/wp-content/uploads/2022/08/Biodiversity-credit-methodology-1.5.pdf
World Wildlife Fund (WWF) Namibia Wildlife 'credits'	Mammals only	Sightings of indicator species	Change in wildlife presence in habitat corridors	Local communities gain monetary benefits, no tradeable credit or reference	https://wildlifecredits.com/
Terrasos biodiversity 'credits'	Protected habitat only	Not applicable	10 m^2 for 30 years	Offsetting for habitat, no monitoring	https://climatetrade.com/climatetrade-and-terrasos-jointly-promote-voluntary-biodiversity-credits-to-support-biodiversity-conservation/
South pole EcoAustralia carbon+ biodiversity 'credits'	Aboveground carbon (gold standard) and Australian native habitat	Not applicable; carbon: gold standard	1.5 m^2 of protected Australian vegetation; carbon: 1 t CO_2-eq	Offsetting for habitat, no monitoring	https://www.southpole.com/sustainability-solutions/ecoaustralia
REDD+[c] carbon projects	Aboveground carbon only; biodiversity not developed[b]	carbon projects must follow standards for biodiversity (Pitman, 2011)	Not applicable	Carbon project revenues used for rainforest protection	https://www.redd.plus/
Verra carbon projects	Aboveground carbon only; biodiversity under development[b]	new carbon projects must follow standards for biodiversity (VCS, 2017)	Not applicable	ca. 75% of carbon projects follow standards for biodiversity	https://verra.org/programs/ccbs/
Gold standard carbon projects	Aboveground carbon only; biodiversity not developed[b]	Not applicable	Not applicable	Safeguarding principles for ecosystem services	https://www.goldstandard.org/our-story/sector-land-use-activities-nature-based-solutions
CORSIA[d] carbon projects	Aboveground carbon only; biodiversity not developed	Not applicable	Not applicable	Biodiversity-rich areas not included in carbon projects	https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx
Plan vivo carbon projects	Aboveground carbon only; biodiversity being developed[a]	Carbon projects must assess biodiversity risks and do no harm	Not applicable	Biodiversity-friendly carbon projects	https://www.planvivo.org/

(Continues)

TABLE 1 (Continued)

Certification scheme	Carbon and biodiversity assessment	Methodology for biodiversity	Biodiversity measurement units	Comments on biodiversity	Reference
Climate action reserve carbon projects	Aboveground carbon only; biodiversity not developed	Carbon projects must follow sustainable forestry practices	Not applicable	Ecologically sustainable carbon projects	https://www.climateactionreserve.org/

Abbreviation: CORSIA, carbon offsetting and reduction scheme for international aviation.
[a]Confirmed by personal communication in May 2023.
[b]Confirmed by personal communication in December 2022.
[c]REDD+.
[d]Reducing emissions from deforestation and forest degradation in developing countries, plus additional climate-friendly, forest-related activities such as sustainable management of forests and the conservation and enhancement of forest carbon stocks.

org/ebvs/indicators), the lack of consensus around biodiversity baselines (Mehrabi & Naidoo, 2022) and the difficulties in accurately surveying and quantifying biodiversity (Bull et al., 2022; Coles, 2023) compared with estimating carbon sequestration potential. Here, we explore what we call a biodiversity and carbon co-crediting system and discuss how its implementation could support conservation and restoration efforts to help societies achieve a greener road to climate and nature positive—moving beyond a state of balance between negative and positive anthropogenic impacts.

2 | THE BIODIVERSITY-CARBON CO-CREDITING SYSTEM

We propose that biodiversity should be explicitly incorporated into carbon crediting schemes to increase environmental and social sustainability in land use. We believe that integrating biodiversity and carbon crediting is important for the following reasons: (1) reducing potential harm to biodiversity in traditional carbon projects such as excess fertilisation and planting monocultures that strongly favour carbon over biodiversity (Lindenmayer et al., 2012); (2) generating market products that maximise the benefits of both compartments in the first place (i.e., planning actions that promote both carbon and biodiversity rather than finding ways to benefit biodiversity under the maximum-carbon scheme, such as monocultures of fastest-growing tree species); (3) reducing overall maintenance costs (e.g., management and measurement); and 4) simplifying regulatory issues.

For this integration to become possible, biodiversity needs to be robustly and efficiently measured (Coles, 2023). This is necessary for assessments of how various forms of intervention (such as reforestation, habitat restoration, agroforestry, etc.) may affect biodiversity as compared to previous land use or management practice. A framework that directly integrates carbon and biodiversity credits needs to be practical and well-tested, setting clear rules that are easy to follow (e.g., Di Sacco et al., 2021). From a global perspective, these rules would benefit from general biodiversity policies (Otero et al., 2020).

How can metrics of biodiversity be aligned with carbon markets? Previous research has shown that market-based incentives can be important mechanisms for driving conservation policy (Pagiola, 2008). Integrating biodiversity credits into existing or novel carbon crediting mechanisms could encourage landowners to proactively manage their land in a sustainable manner. If biodiversity and carbon are rewarded in the same scheme, land managers are more likely to optimise different types of benefits for the particular land cover in the region (Bryan et al., 2016; Thomas et al., 2013). For instance, today only net gains in carbon are quantified within carbon offsetting schemes, which directly incentivises cutting and reforestation instead of protecting a forest from felling in the first place (Figure 1). Restoring rather than protecting is usually a significantly worse and more expensive solution in both biodiversity and carbon storage terms, given the manifold advantages of an old-growth forest as compared to tree planting or natural regeneration. Today, many carbon crediting schemes are blindly focused on 'cheap carbon', supporting interventions that in fact lead

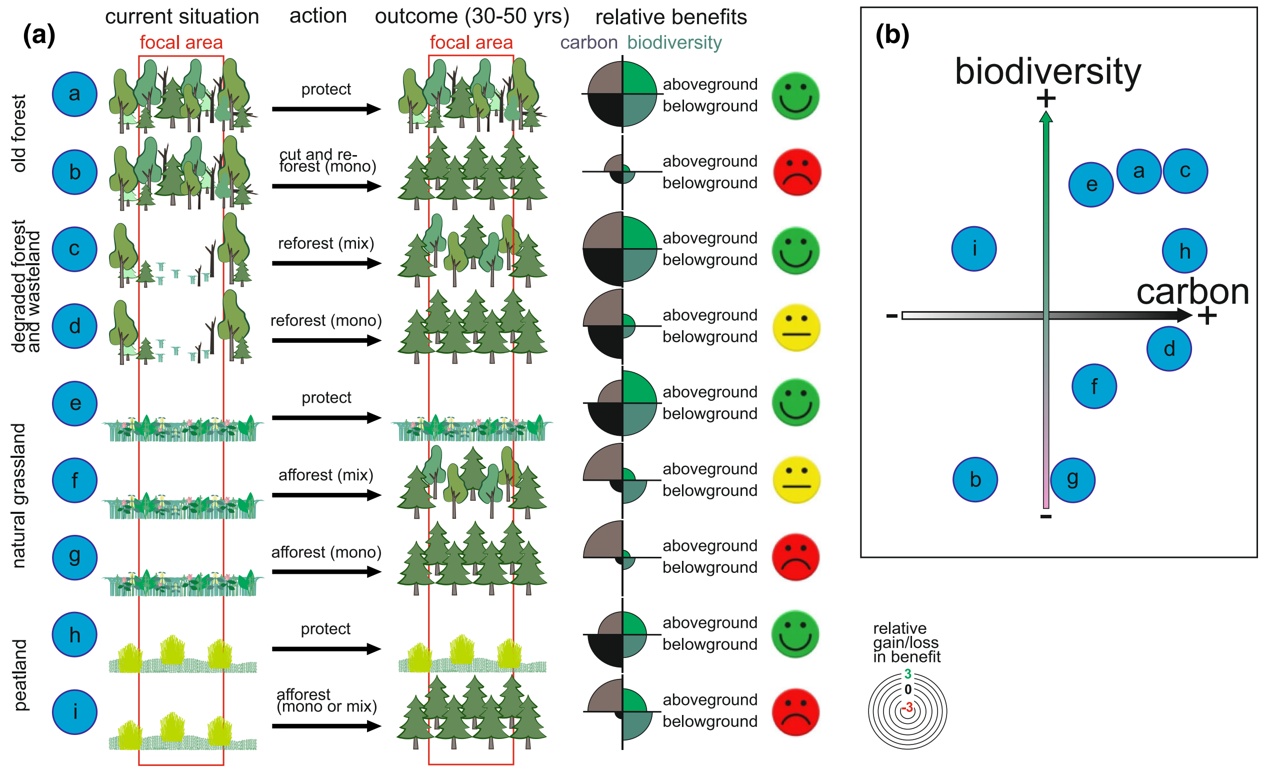

FIGURE 1 Schematic representation of relative carbon and biodiversity net changes from protection, reforestation and afforestation of various ecosystem types (given as circles with small letters): (a) changes in aboveground and belowground carbon and biodiversity; and (b) trade-offs (including win-win and lose-lose situations) of these interventions from the biodiversity and carbon perspectives. In (a), the size of the relative benefits circle indicates worsening (small circles) or improvement (large circles) of above- and belowground carbon (left half) and biodiversity (right half). These estimates are based on the data and interpretations from Pitman (2011), James and Harrison (2016), Lewis et al. (2019), Tedersoo et al. (2020), Camia et al. (2021), Di Sacco et al. (2021) and Andres et al. (2023).

to the lowest levels of both carbon storage and biodiversity in the medium term (Figure 1). Therefore, all carbon offsets and credits affecting land use and land cover should have baseline estimates for their effects on biodiversity.

3 | BIODIVERSITY PROXIES

In many ecosystems, such as forests, biodiversity is difficult and costly to comprehensively estimate across multiple components and layers such, as soil, wood, air and tree canopy. Recent advances in high-throughput DNA sequencing analysis of environmental samples (eDNA analysis) offer a promising tool for rapid, cost-effective evaluation of biodiversity, a technique now thoroughly validated for water, soil and bulk animal samples (Taberlet et al., 2018). eDNA-based biodiversity assessments are becoming more feasible on a larger scale, and the approach is well validated (Ji et al., 2013; Taberlet et al., 2018). The eDNA approach helps in encapsulating a much larger proportion of the planet's biodiversity than previously possible through visual assessments.

Because soil contributes to a vast proportion of biodiversity (most terrestrial species have at least part of their life cycle underground), productivity and functioning of terrestrial ecosystems (Wardle, 2002; Yang et al., 2018), soil biodiversity constitutes a proxy for biodiversity and ecosystem health in most forest, grassland and agricultural habitats (Orgiazzi et al., 2016). Soil biodiversity analyses follow the HANDY principle—they are high-tech, accurate, novel, detailed and yielding. Comprehensive assessment of soil biodiversity, including both macro- and microorganisms, can be carried out using an internationally standardised soil sampling scheme (e.g., SoilBON) coupled with cross-kingdom global analyses of soil biota (Bahram et al., 2022; Guerra et al., 2022; Ritter et al., 2019). Such analyses can also help us develop a better global picture of cryptic biodiversity, such as where hotspots of micro-organismal diversity are located (Guerra et al., 2022; Orgiazzi et al., 2016; Tedersoo et al., 2020). Using soil biodiversity as a metric to evaluate the impact of reforestation and habitat restoration increases the ease of measuring, comparing and monitoring biodiversity across diverse landscapes and over time (Jiao et al., 2018).

Soil biodiversity analyses are also able to measure multiple components of biodiversity, including genes, species, functions, evolution and ecosystems (Antonelli, 2022). Because genes and individuals are more difficult to measure and species are easier to grasp, species-level metrics have received the greatest public and conservational interest, with species richness, effective number of species and multidiversity as the best biodiversity proxies (Allan et al., 2014; Chao et al., 2014).

Functional and evolutionary (phylogenetic) diversity offer additional insights into ecosystem functioning (Cadotte et al., 2011), and although both can be approximated through eDNA analyses, ascertaining impacts on ecosystem functions requires further information about the ecology of individual species, which is lacking for most soil organisms.

Species also differ in abundance, which in turn affects their contributions to ecosystem functioning. The redundancy and additionality of rare species can be difficult to assess due to the low statistical power of observational studies. Also here, eDNA analyses have been shown to succeed well in detecting rare species when appropriate protocols are used (Geml et al., 2014; Xia et al., 2021). Rare species are often habitat specialists or sensitive to anthropogenic impact (Dee et al., 2019). Therefore, rare, especially threatened species, can be considered more important from conservation and crediting perspectives (Brooks et al., 2006; The Wallacea Trust, 2022). However, the conservation status of the vast majority of species has not yet been formally assessed (IUCN, 2022). One pragmatic approach is to weigh the importance of all species equally, until we can rank all species based on their conservation importance (i.e., rarity and vulnerability to global change) or distinguish them by function (e.g., species delivering specific ecosystem services), origin (e.g., endemic, native and invasive species) and habitat (e.g., old forest specialists and keystone forest species in reforestation projects) (Coles, 2023; Kõljalg et al., 2022). Rapidly growing traits and occurrence data portals such as the Global Biodiversity Information Facility (www.gbif.org), the TRY Plant Trait Database (www.try-db.org) and FungalTraits (Põlme et al., 2020) may facilitate the identification of target species for ecosystem restoration in the near future.

4 | LIMITATIONS AND OPPORTUNITIES FOR eDNA

While eDNA analyses provide a data-rich, cost-effective and standardised framework for assessing biodiversity, like any method, they too have inherent limitations. The DNA of dead organisms (such as animals or trees that died many years prior to the soil sampling) and from wind-dispersed organisms (such as pollen and spores from kilometres away) may blur the assessment of active and living organisms at a particular site (Carini et al., 2020). The available eDNA metabarcodes do not cover all organisms because of global and regional imbalances in the generation and public availability of reference datasets, primer-template mismatches, the presence of introns and insufficient taxonomic resolution in certain groups and difficulties in capturing large organisms such as top predators. While these issues can be partly ameliorated by using long DNA fragments (Tedersoo et al., 2021), current technologies do not address the spatial and temporal heterogeneity of communities, which are generally poorly known at fine scales and may differ across habitats (Bahram et al., 2015). Furthermore, it may be difficult to preserve samples for eDNA analyses in remote areas and to perform the highest-quality analyses in countries with insufficient laboratory infrastructure.

Given such shortcomings in the use of eDNA, additional standardised, semi-automated technologies can be used for recording images and/or sounds of mammals and birds, followed by identification using machine learning techniques, and complemented by standardised sampling of other taxonomic groups through insect traps and spore samplers (e.g., https://www2.helsinki.fi/en/projects/lifeplan; The Wallacea Trust, 2022). Besides routine aboveground carbon monitoring (Zhang et al., 2022), remote sensing can be used to determine some aspects of biodiversity, such as tree diversity, evaluating implementation of management practices and disturbances across the entire project. However, remote sensing is unsuitable for biodiversity assessment of animals and small organisms (Cavender-Bares et al., 2022). The complexity of the analyses may also warrant the presence on-site of part-time technicians, and biodiversity and carbon specialists need to carefully oversee and occasionally ground-truth remote-sensed assessments as well as those obtained from eDNA analyses. Independent verification is also crucial to ensure the credibility and reproducibility of biodiversity and carbon assessments, in particular to support the implementation of any certification schemes.

5 | THE CO-CREDITING PROCESS

To maximise biodiversity and carbon benefits, a robust co-crediting system could deploy evidence-based criteria for the selection of areas for potential conservation and restoration using a combination of field surveys, remote sensing, soil maps and machine learning algorithms (Silvestro et al., 2022). Rewarding companies and communities for positive change requires a robust monitoring, evaluation and reporting framework that captures demonstrable improvements in biodiversity.

In the process of land evaluation, we propose that representative plots are randomly surveyed by accredited institutions using standardised procedures that are verified independently (Michaelowa et al., 2019). The representative plots for monitoring should be of sufficient size and number and located randomly in the survey area, avoiding edge effects. The sampling standards may follow well-elaborated protocols for large-scale sampling schemes, such as SoilBON (https://www.globalsoilbiodiversity.org/soilbon), but these may differ by project, considering representativeness of sampling, type of habitat and target organisms, among other aspects. Sampling should capture a significant proportion of biodiversity, and optimal sampling intensity should be determined based on pilot studies or information from the scientific literature. It is important to consider the time of sampling (in the growing or wet season) and storage of samples to avoid loss or alteration of diversity through DNA degradation (Taberlet et al., 2018) in order to enhance comparability across time. Molecular analysis of as many taxonomic groups as possible—plants, animals, fungi, micro-eukaryotes and prokaryotes—offers the most accurate views on overall biodiversity, reducing taxon-specific biases (Allan et al., 2014).

The carbon-biodiversity co-benefits can be calculated based on temporal changes relative to control plots and near-natural reference plots (endpoints) to account for climatic differences and batch effects (i.e., temporal sampling differences). The control plots should occur in comparable vegetation in nearby lands not affected by the interventions being evaluated and reflect a situation of average management intensity, or the 'business as usual' scenario—how carbon and biodiversity would have changed without the intervention applied (Figure 2). It is important to perform temporal sampling in the same representative and control plots to minimise analytical error and provide feedback about the best and worst performing areas (while keeping plot localities undisclosed).

Coupled with monitoring biodiversity, soil carbon can be additionally estimated using deep cores to include subsoil (Figure 2). As most carbon crediting schemes account only for aboveground biomass production, carbon storage in soil remains usually overlooked. In some regions, topsoil carbon stocks alone are comparable in size to aboveground carbon but vary greatly across biomes and land cover types (Scharlemann et al., 2014), such as lower biomass accumulation in nutrient-poor rainforests. Soil carbon stores also tend to increase with sustainable land management, including organic farming, moderate grazing pressure, selective timber harvesting and the establishment of mixed plantations (Chaudhary et al., 2017; Chen et al., 2023; Jackson et al., 2017; Schroth et al., 2002).

Biodiversity monitoring can be performed in 5- to 10-year intervals, which is a typical time frame in carbon crediting businesses (Michaelowa et al., 2019). Biodiversity and carbon crediting mechanisms should secure longevity, that is, the potential to prolong contracts for decades or centuries—instead of the mere 30 years currently used under most carbon crediting schemes. Upgrading initial contracts to higher-value ones should also be considered, for example, for young forests that become more highly valued when they become old and support more biodiversity and soil carbon. To maintain such a long-term monitoring process, project managers should take care of proper storage of materials and data. Carefully preserved DNA samples can be reused decades later when better DNA sequencing methods emerge or when additional taxonomic groups or markers are added for a more comprehensive analysis of biodiversity. Currently, molecular analysis of soil samples from 100 plots (corresponding to a

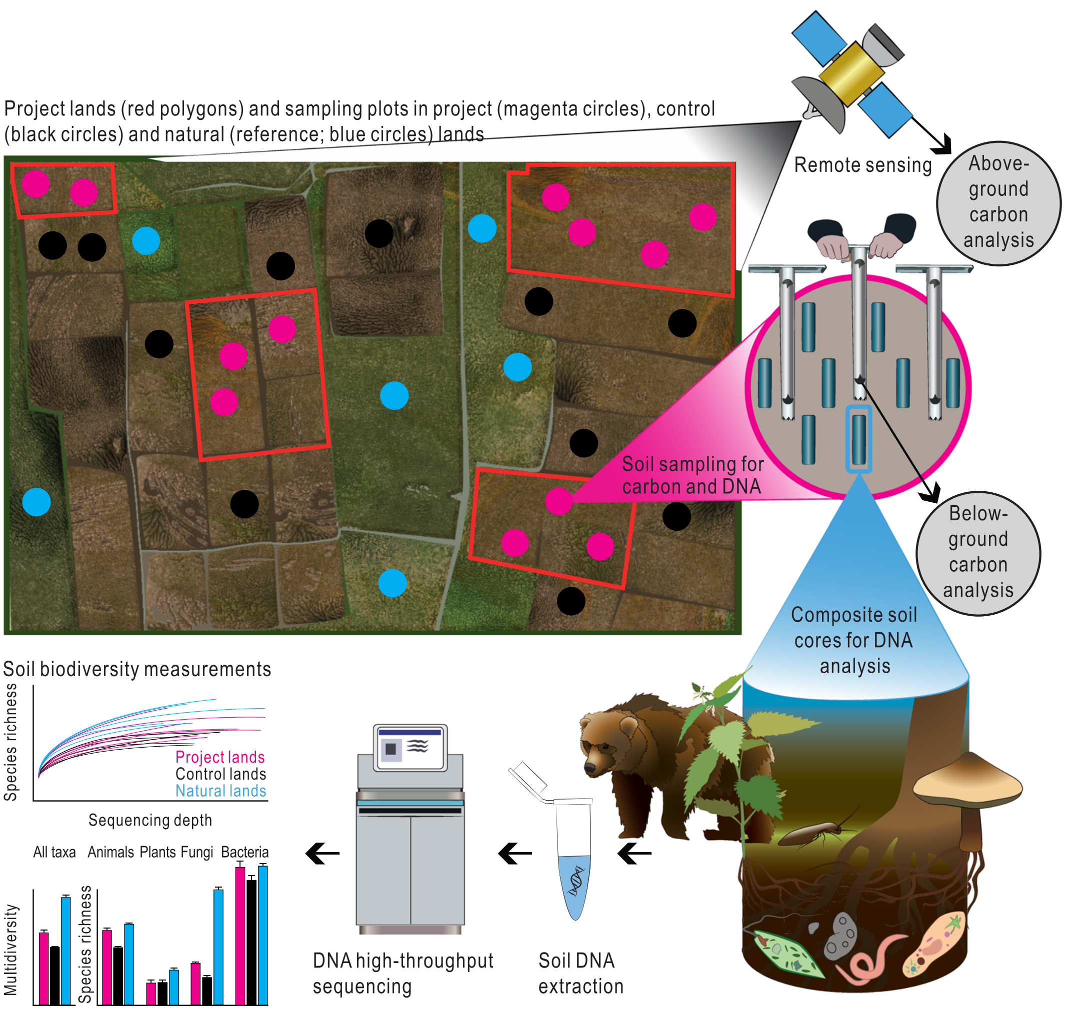

FIGURE 2 Analytical workflow of above- and belowground carbon and soil eDNA analysis for carbon-biodiversity co-crediting. Representative plots are randomly established on project lands, control and natural reference sites and subjected to eDNA-based biodiversity monitoring, soil carbon and aboveground carbon assessment based on remote sensing and core-based chemical analysis, respectively. The weighted results of multidiversity increase and carbon sequestration across 5 years determine the number of credits to be issued.

medium-size project) costs 3000 Euros upwards, but sequencing costs per unit of data continue to decline.

Carbon crediting is based on one ton of CO_2 equivalent removed or emissions prevented. Therefore, for integrating biodiversity into the carbon crediting system, we propose that the metric for biodiversity crediting should also be quantitative. The Wallacea Trust (2022) suggested that a 1% uplift of biodiversity relative to reference sites per hectare represents a suitable measure for relative biodiversity change. We agree with the suggestion, but it is important to add a timescale for the change—which we propose as 1 year for many environments and calculated on average from multiple years.

Crediting institutions should release credits after data analysis and verification rather than based on future pledges, although ex-ante payments should be considered to reduce poverty in low- and middle-income countries (Porras & Steele, 2020). Occasional verification must be performed by independent assessors to secure the transparency and validity of approaches and measurements. The weighting of carbon and biodiversity components should remain flexible because of potentially changing stakeholder expectations over time and across regions. We envision both a fixed component (e.g., 25% for carbon and 25% for biodiversity) and a flexible band reflecting stakeholders' expectations, which may differ for conservation and restoration programmes. Such flexibility and complementarity of the co-crediting components is crucial; for example, a project that maintains or restores a natural savanna may, for instance, not capture as much carbon as a new tree plantation but help preserve highly threatened biodiversity.

6 | TRADING PARTIES

While carbon credits are issued by international and national governmental organisations, biodiversity credits can be issued by parties that own or lease land and are interested in long-term conservation and income, for example, governments, private and corporate landowners, non-governmental organisations and indigenous and other local communities. Hence, for co-crediting, private issuers could collaborate with local governments or buy carbon credits to sell co-credits. Buyers of these credits may include conservation-aware companies and individuals, such as those from the tourism sector and philanthropists, as well as private resellers, that is, parties acting in the carbon and developing biodiversity markets. Biodiversity and carbon co-credits are also suitable for private and corporate investors because their value is likely to rise with increasing global change and deteriorating biodiversity worldwide. To avoid offsetting claims not linked to concrete reductions in carbon emissions and environmental damage—'greenwashing'—companies with harmful actions on climate and nature as identified by an ethical committee or the conservation community could be excluded from this trade. Trading could be performed via tokens in banks, as implemented for carbon credits and offsets.

Because much of the conserved and restorable land around the world is suitable for supporting biodiversity-carbon co-crediting, it is of utmost importance that any monetary benefits are shared with local communities, including indigenous peoples, who have been the main stewards of biodiversity and should be the primary beneficiaries of the co-crediting system proposed here. Benefits should include both monetary revenues and involvement through performing sustainable management practices, guarding of project areas and avoiding certain unsustainable practices, such as slash-and-burn agriculture and landscape burning to ease hunting.

7 | CONCLUSION

The urgency for our societies to become climate and nature positive in the shortest possible time is triggering vast investments and initiatives around the world. However, trying to combat one major challenge (climate change) while making another one worse (biodiversity loss) would represent a huge opportunity loss. The inclusion, valuation and validation of biodiversity and other functional and ecosystem service-related co-benefits within carbon crediting schemes will help reduce global biodiversity loss by incentivising actions that promote biodiversity in carbon sequestration projects (Thomas et al., 2013). Here we propose to evaluate both aboveground and belowground carbon and monitor biodiversity using combined eDNA, audio and remote sensing approaches. While the methodology and data sources we highlight constitute a solid foundation for a carbon and biodiversity co-crediting system, we acknowledge that there is not yet full scientific consensus about the reliability of eDNA analyses for precise, temporal biodiversity assessments, which means that further testing and validation are required by researchers and companies. Given the increasing attention on biodiversity, as demonstrated under the United Nations Biodiversity Summit (COP15) in December 2022 and the adoption of the Kunming-Montreal Global Biodiversity Framework, it is likely that the relative valuation of biodiversity will increase compared with carbon, especially when high-income countries reach their emissions reduction goals. Monetary biodiversity and climate co-credits will promote environmentally sustainable stewardship of land globally and contribute much of the global financing for conservation and ecosystem restoration (Deutz et al., 2020).

AUTHOR CONTRIBUTIONS

Leho Tedersoo and Jaan Sepping generated the initial concept. Alexey S. Morgunov, Martin Kiik, Kristiina Esop, Raul Rosenvald, Kate Hardwick, Elinor Breman, Rachel Purdon, Ben Groom, Frank Venmans, E. Toby Kiers and Alexandre Antonelli further developed the concept from various perspectives. Leho Tedersoo, E. Toby Kiers and Alexandre Antonelli wrote the manuscript, with contributions from all authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article because no new data were generated or analysed in this study.

ETHICS STATEMENT

The authors confirm that the research is in accordance with ethics principles.

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