Towards Nature Positive supply chains: From biodiversity impacts to organisational action

Authors:

Éilish Farrelly[1,2*], Talitha Bromwich[1,2,3], Sophus zu Ermgassen[1,2,4], Joseph Bull[1,2], Hollie Booth[1,2], Heather Needham[5], Alice Karuri[6], Samuel Thuo Mungai[7], Kamau Mbarire[7], Thomas White[1,2,8], Emily Stott[2], Charlotte Maddinson[9] and E.J. Milner-Gulland[1,2].

*Corresponding author email: eilish.farrelly@biology.ox.ac.uk

Institutions:

[1]Leverhulme Centre for Nature Recovery, University of Oxford, Oxford, UK

[2]Interdisciplinary Centre for Conservation Science, Department of Biology, University of Oxford, Oxford, UK

[3]Smith School of Enterprise and the Environment, University of Oxford, Oxford, UK

[4]Oxford Earth, University of Oxford, Oxford, UK

[5]Environmental Sustainability, Estates Services, University of Oxford, Oxford, UK

[6]Strathmore University, Kenya

[7]Agri-Solutions Enterprises Ltd, Kenya

[8]The Biodiversity Consultancy, Cambridge, UK

[9]School of Resource Wisdom, University of Jyväskylä, Jyväskylä, Finland

Abstract

Large organisations are critical to halting and reversing biodiversity loss, yet most of their impacts are hidden in complex supply chains. Robust strategies to fully identify, quantify, trace, and begin to mitigate these impacts remain rare. Here we present a generalisable workflow for assessing and addressing supply chain impacts on biodiversity and then apply it to the University of Oxford's biodiversity impacts. We show how organisations can evaluate traceability and transparency in their supply chains, estimate region-specific biodiversity impacts, and harness collaborations for impact mitigation. Among Oxford's 131 highest-spend suppliers, only 18 disclosed raw material origins and just two offered product life cycle assessments, evidencing the major traceability gap and underscoring the systemic barriers to accountability and need for supplier engagement. Using Oxford's coffee supply chain as a case study, we apply life cycle impact assessment to estimate the coffee procurement biodiversity footprint and demonstrate how collaborations could translate these insights into practical interventions. By shifting the focus beyond diagnosing supply chains as a major driver of biodiversity loss to delivering actionable solutions, this study provides a scalable pathway for large organisations to contribute to global nature recovery.

Main

Organisations are increasingly articulating commitments to action on nature and exploring approaches to measure their biodiversity impacts and dependencies, in response to policy expectations and growing awareness of the social and economic risks of nature loss[1-5]. Yet despite this momentum and the critical role organisations must play, there remains little clarity on how they can translate ambition into credible, applicable steps for the majority of their biodiversity footprint, which often lies upstream in complex and opaque supply chains[6-11]. Here, we demonstrate a practical and defensible pathway for organisations to reduce harm, generate positive outcomes, and contribute to systemic change, towards a Nature Positive future[12].

Supply chains typically have low traceability (i.e., ability to determine product origins) and transparency (i.e., disclosure of product information), making it difficult to link procured products to on-the-ground biodiversity impacts and accurately quantify associated losses[13-15]. This hinders information flow along value chains and limits the design of effective mitigation strategies, including appropriate prioritisation and justification of interventions[16,17]. While platforms such as Trase and Open SC improve traceability by mapping global commodity flows, they are limited by a focus on agricultural commodities and their operation at national or regional scales[18-20]. Bottom-up mitigation approaches developed by and for individual organisations and their supplier networks to address supply chain impacts remain rare yet are essential for delivering meaningful and measurable outcomes.

Existing guidelines for addressing organisational impacts prioritise the prevention of impacts (i.e., avoidance and reduction) ahead of compensatory actions (i.e. restoration and offsetting) in line with the Mitigation Hierarchy[21]. The Science-Based Targets for Nature (SBTN) emphasise this by explicitly excluding compensatory actions and offsets within the Land standard, currently the most developed SBTN domain[22]. In practice, this prioritisation requires organisations to interrogate what is considered "mission-critical" and to pursue avoidance and reduction strategies wherever possible. This may include actions such as zero-deforestation commitments in supply chains, sourcing certified produce with lower biodiversity impacts, reducing waste, reducing overall material consumption, and promoting circular use of materials (e.g. mandating refurbished IT and furniture), for which environmental benefits have been demonstrated in the case of laptops[23-26]. Nonetheless, even under ambitious avoidance and reduction strategies, certain products are likely to continue exerting unavoidable pressures on biodiversity[27]. Consistent with this, the biodiversity footprint assessment of the University of Oxford shows that even under a high-avoidance scenario, one third of the business-as-usual biodiversity footprint remains as residual impact requiring compensatory action[7].

As organisations set more ambitious Nature Positive commitments, there is therefore a growing need for guidance to ensure that compensatory actions for unavoidable and residual supply chain impacts are credible, transparent, and deliver lasting biodiversity gains, as equivalent as possible to the original negative impacts[28]. While actions to avoid and minimise impacts are well defined (e.g. through SBTN), far less clarity exists on how organisations should implement positive actions to compensate for biodiversity impacts when uncertainties are high, and losses and gains are difficult to match[29].

A key source of uncertainty lies in the methods commonly used to quantify and compare biodiversity impacts across supply chains. Generic life cycle assessments (LCA) are a widely applied method, used by organisations to assess and compare the relative biodiversity impacts of different activity streams, enabling prioritisation of impact categories that require more detailed investigation[30-33]. However, these approaches are often not spatially explicit and have numerous sources of uncertainty. For example, outputs are typically averaged across large regions. This limits the usefulness of LCA outputs to justify actions, and for the design of distinct, spatially explicit mitigation and conservation actions that can compensate for impact.

Here, by contrast, we take a bottom-up approach to examine the biodiversity impacts of an organisation's supply chains and identify how these impacts can be addressed through targeted, actionable mitigation and conservation. We build on Bull et al. (2022), which demonstrated that most of the University of Oxford's biodiversity footprint arises from its supply chains, but left unresolved how such impacts might be traced to a finer spatial scale and mitigated in ways that contribute to a Nature Positive future. We structure the analysis using the Mitigation and Conservation Hierarchy (MCH), which provides a framework for addressing dispersed impacts across complex supply chains, not only helping to prevent inaction where residual impacts cannot be directly offset, but also supporting systemic and transformational change towards Nature Positive outcomes[34,35].

After assessing the traceability and transparency of the University of Oxford's major supply chains, we focus on coffee as a single case study product to demonstrate approaches for estimating the biodiversity footprint of a key raw commodity at source. We then evaluate mitigation and conservation opportunities to address these impacts with in-country collaborators. This analysis informs the development of a generalised workflow applicable to other products procured by the University of Oxford, and to other organisations more broadly (Fig.1).

We do not assume numerical equivalence between upstream, life-cycle-based supply chain impacts and actual impacts, as this risks oversimplifying ecological complexity, and is widely recognised as practically unfeasible[31,36]. Decision-making frameworks that rely on averaged or model-derived impacts are inherently constrained in their ability to guide credible compensatory action, as they detach impacts away from the actors, locations and decisions required to address them. In response, we use the MCH to identify feasible, evidence-based interventions across the supply chain and demonstrate how organisations can progress from impact measurement to prioritised action. Although more analytically demanding than approaches based on averages, this workflow increases ecological and spatial alignment between supply chain impacts and mitigation and conservation actions by grounding decisions in actual sourcing relationships. This subsequently enables more proportionate, transparent, and on-the-ground responses to biodiversity loss.

Fig. 1: Generalised Workflow

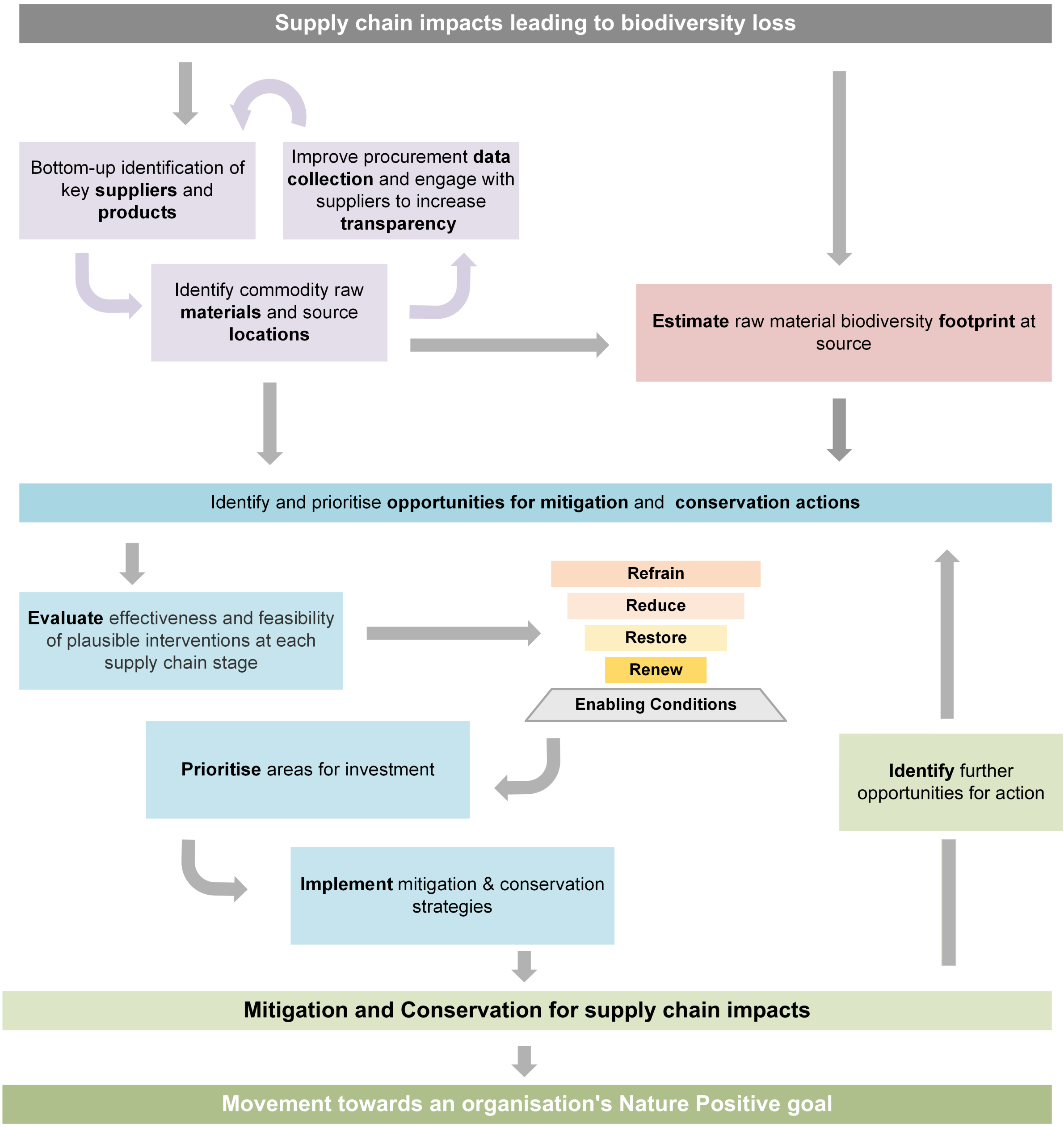


Figure 1: Generalised workflow for addressing biodiversity impacts in organisational supply chains, in support of Nature Positive goals. The workflow links supply chain traceability and transparency with mitigation and conservation action through the Mitigation and Conservation Hierarchy (MCH). Colours denote the main analytical components, with traceability and raw material mapping shown in parallel to reflect that these processes can occur simultaneously. Purple arrows indicate how increased supplier engagement and data transparency can improve understanding of raw material origins, enabling targeted interventions to reduce upstream biodiversity pressures. The inverted pyramid illustrates the MCH stages (Refrain, Reduce, Restore, Renew), supported by enabling conditions that facilitate action but do not directly generate biodiversity benefits. Applied to the University of Oxford's supply chains, the workflow highlights how existing collaborations can support the identification and implementation of mitigation and conservation opportunities.

Assessing traceability and transparency

We assessed traceability and transparency across the University of Oxford's research, operations, and construction supply chains, corresponding to the first stage of our workflow (Fig. 1; see Methods and Supplementary Information S1 for details). This analysis aimed to determine the origin and composition of the University's highest-expenditure products, identifying where procurement activities may exert pressure on biodiversity globally.

The results revealed a pronounced traceability gap, reflecting a fundamental challenge that organisations face in addressing biodiversity impacts (Fig. 2; Supplementary Information S1.8). Despite substantial efforts to contact all 131 highest-expenditure suppliers, this was possible for only 67% (88 suppliers) due to incomplete invoice records or missing contact information, and only half of those contacted responded. Eighteen suppliers identified product origins or raw materials for at least one item that they supply to the university, but only two suppliers (<2%) shared complete information for at least one item, including sourcing locations, raw materials, and LCA data. Both of these items belonged to the "Office, Classroom, Library and Outdoor Furniture" subcategory within the operations supply chain. This sharp decline of data availability and supplier engagement at each stage of data collection indicates a progressive loss of traceability and transparency from initial contact through to final acquisition of raw material and life cycle data (Fig. 2). The extensive organisational effort and repeated outreach required to obtain even partial data from suppliers highlights the substantial resource burden of this process, which itself constitutes a major constraint on achieving full supply chain transparency and traceability.

Fig. 2: Traceability and Transparency along the Supply Chain

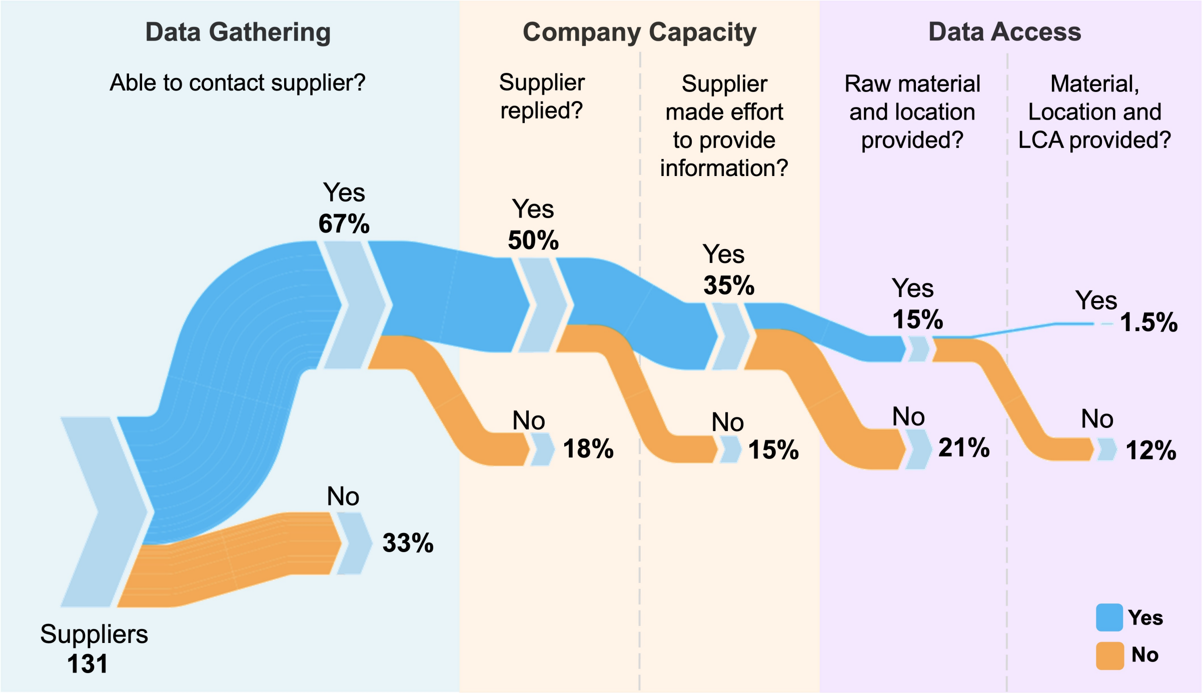


Figure 2: Decline in supply chain traceability and transparency across the University of Oxford's procurement categories. Sankey diagram illustrates the progressive loss of traceability and transparency across research, operations and construction supply chains, structured into three stages: "Data Gathering" (ability of researchers to contact suppliers), "Company Capacity" (supplier response and willingness to provide information), and "Data Access" (provision of raw material, location, and life cycle data). Blue and orange flows indicate "yes" and "no" responses, respectively, at each stage.

The structure of supply chains combines vertical complexity (multiple tiers of suppliers) with horizontal complexity (diverse raw materials sourced across regions)[37,38]. Within the University of Oxford's procurement network, 42 suppliers (48%) acted as distributors rather than manufacturers (i.e. companies that sell products made by others), increasing vertical complexity by adding distance from production sources[39]. Only 15 distributors were willing to contact upstream suppliers, indicating limited transparency beyond first-tier relationships. Increased provision of data was therefore concentrated among suppliers operating in simpler product categories, with the two suppliers providing complete data belonging to a furniture subcategory characterised by fewer components and more localised sourcing.

Confidentiality was the most frequently reported barrier to information disclosure, where nearly half of suppliers (48%) declined or were unable to share data on raw material composition, and 43% did not provide sourcing locations. Only five suppliers collected or shared LCA data, and this was limited to carbon footprints. Together, these results indicate the systemic opacity of organisational supply chains, driven by limited traceability, weak upstream engagement, confidentiality barriers, and the absence of governance structures providing clear expectations for transparency[40,41,15]. Addressing these constraints will require both stronger supplier engagement and standardised data collection protocols, which record not only financial expenditure but also product weight and quantity. In addition, material composition and sourcing geography should be captured, and underpinned by governance mechanisms and legal requirements that create clearer expectations for disclosure and accountability. Such information is essential for more granular estimation of biodiversity impacts and for the design of targeted interventions towards Nature Positive outcomes.

To demonstrate how improved data availability can inform action, we chose a single commodity - coffee - for deeper investigation. We selected coffee as it is a raw (rather than composite) product with high biodiversity impact, high socioeconomic importance, and is partially traceable to the country-level within the Oxford purchasing system[42-45]. This enabled us to demonstrate how knowledge of sourcing regions can be used to estimate biodiversity impacts using established life cycle impact assessment (LCIA) methods[7,30].

Estimating coffee’s biodiversity footprint

For the 2022-23 financial year, the University of Oxford’s coffee purchases were associated with a total estimated biodiversity footprint of 2.68×10^{-9} PDF·year, aggregated across the three sourcing regions (the “potentially disappeared fraction” of species, estimated to be lost over one year due to environmental impacts such as land use, climate change etc., quantified using LCIA approaches; see Methods)[46]. The three University of Oxford coffee sourcing regions had marked differences in both the estimated magnitude and composition of environmental impact pathways (Fig. 3). Coffee sourced from East Africa had the largest estimated biodiversity footprint (1.81×10^{-9} PDF.year), around three times higher than if sourced from Central America and six times higher than South America. This difference was driven primarily by the greater land use requirements per kilogram in the LCA data used to estimate impacts of coffee grown in East Africa, making land use the dominant environmental pressure in the region (81%)[47]. In Central America, land use was also the largest contributor (44%), but eutrophication and climate change impacts played proportionally larger roles. In contrast, South America exhibited a distinct profile, with acidification contributing the largest share (28%), and land use being relatively smaller. Across all regions, water use contributed negligibly to overall endpoint biodiversity impacts.

Fig. 3: Coffee's Regional Biodiversity Footprint

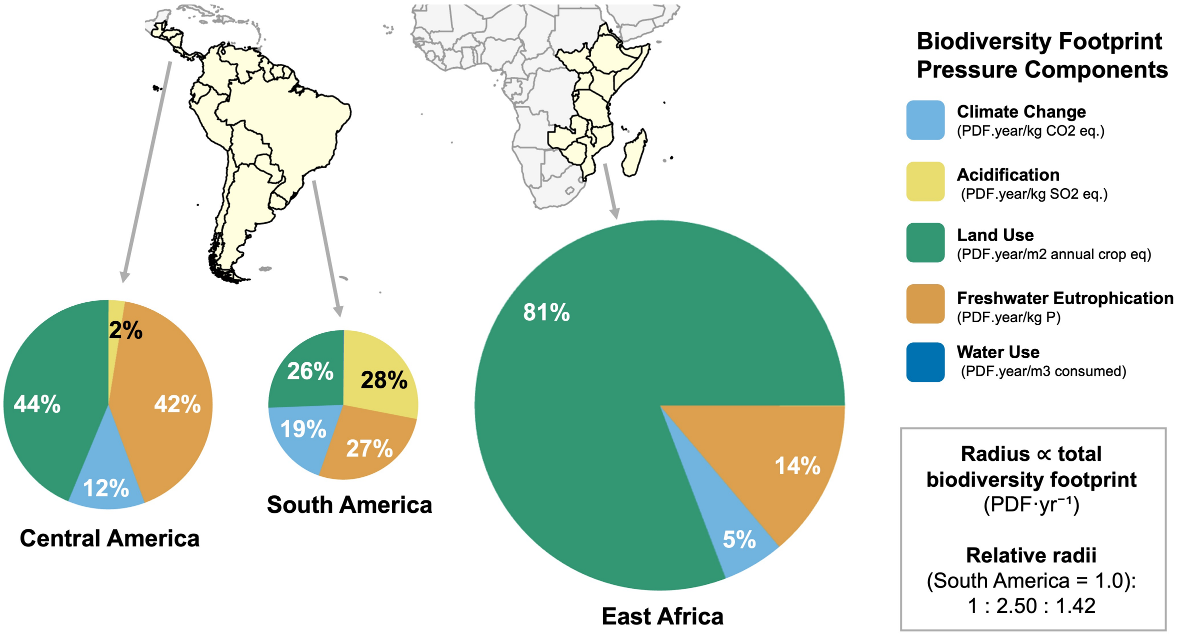


Figure 3: Composition and magnitude of the biodiversity footprint of coffee across sourcing regions. Pie charts show the proportional contributions of five environmental pressures (climate change, acidification, land use, freshwater eutrophication, and water use) to the estimated biodiversity footprint of coffee sourced from Central America, South America, and East Africa. Pie chart radii are scaled to the total biodiversity footprint of each region.

These patterns are consistent with previous work showing that sourcing location strongly influences both the magnitude and nature of biodiversity pressures, including for coffee, where impacts such as carbon footprint and water scarcity vary substantially by origin [48,49]. However, LCIA-based biodiversity footprint estimates carry inherent uncertainties due to variation in model assumptions, data quality, coarse spatial resolution, and category aggregation (see Supplementary Information S2.3 for a sensitivity test comparing estimates across different LCIA models)[31,50]. As such, the values reported here are indicative of relative pressures across sourcing regions rather than precise absolute impacts. Nonetheless, they offer a transparent basis for comparing relative impacts and assessing the potential mitigation benefits of different actions.

Opportunities for targeted mitigation and conservation

Regional variation in biodiversity pressures arising from supply chain activities emphasises the need for locally tailored mitigation and conservation approaches[48,51]. Accordingly, organisations seeking to address biodiversity impacts should identify collaborators in sourcing areas, who can recognise, implement, monitor, and report on locally relevant mitigation actions. These collaboration opportunities will differ between organisations, but could include suppliers, NGOs, researchers, and/or other landowners. We demonstrated how this could be done for a university by reaching out to researchers based at the University of Oxford working both generally on biodiversity and specifically on coffee, to answer a survey about their research collaborations. Researchers were identified through initial contacts and snowball sampling, with respondents asked to highlight other researchers working on coffee- and biodiversity-relevant collaborations. As this was a demonstrative exercise, we did not aim to map all collaborations; however, no additional coffee-related projects emerged during the survey, suggesting saturation within the defined scope.

To contextualise these collaboration opportunities, we first mapped the global distribution of the University of Oxford's raw material suppliers (from the 18 suppliers who provided at least one raw material and source location; Fig. 2; Fig. 4a). We then compared these sourcing locations with reported research collaborations that could support biodiversity mitigation and conservation (Fig. 4b).

The 34 biodiversity and conservation researchers responding to our survey reported 69 collaborations across all inhabited continents. Of these, 47 (68%) indicated they could support supply chain impact mitigation or conservation strategies, including 23 (49%) that either directly involved coffee-related projects or were located within coffee-sourcing regions.

Fig. 4: Global maps of Oxford supplier raw material locations and research collaborations

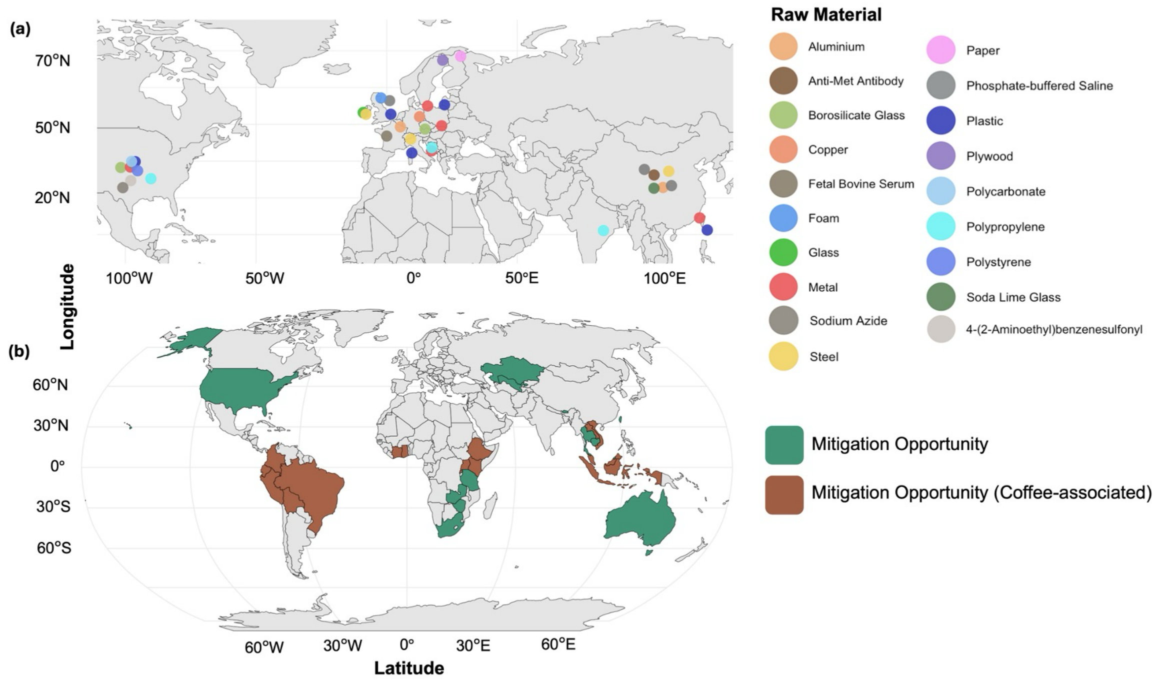


Figure 4: (a) Global distribution of the University of Oxford's raw material suppliers (food supply chain excluded; see Supplementary Information S1.4). Coloured points indicate source locations for materials used across research, operations, and construction supply chains. Points are not scaled by quantity or volume due to incomplete data, and displaced centroids are used to separate overlapping country locations. (b) Countries in which University of Oxford researchers have reported collaborations with potential to support conservation and mitigate biodiversity impacts in the University's supply chains. Green shading indicates general mitigation opportunities, while brown shading denotes coffee-associated opportunities, either through research explicitly focused on coffee or located within coffee-growing areas.

In this particular study, we illustrate Oxford's sourcing locations more generally (Fig. 4a) and then focus on identifying opportunities for mitigation and conservation for coffee only, as this is the focus of our case study (Fig. 4b). As sourcing information improves, these hotspots could be cross-referenced with locations of active research collaborations to identify existing overlaps, or, where appropriate, guide procurement towards regions where strong research ties already exist. Such alignment could facilitate the co-development of locally informed mitigation and conservation strategies, supported by transparent financial flows and monitored through ongoing in-country partnerships (see Supplementary Information S4.1, Fig. S8, for examples of actions and strategies for mitigation of coffee supply chain impacts, aligned with the MCH). Footprint results could also inform longer-term procurement strategies, including shifts away from regions associated with particularly high biodiversity impacts.

Other universities accounted for a large share of both the University of Oxford's general and coffee-specific collaboration opportunities (30 general, 18 coffee-related), while NGOs played a substantial but less coffee-focused role (33 and 13 respectively). Most collaborations were research-oriented (36 general and 17 coffee-related), followed by implementation-focused (22 and 9, respectively). Researchers noted that mitigation-relevant collaborations commonly involved community-based conservation or links with specific farms where interventions could be implemented (Supplementary Information S3.4 Table S18). Beyond direct footprint reduction, such collaborations may also generate indirect positive outcomes for biodiversity, often referred to as "handprints"[52]. For example, research and monitoring activities could contribute improved knowledge of how to design effective mitigation and conservation actions, which could then be used by others. Additionally, such collaborations could be structured as equitable and inclusive partnerships providing mutual benefits (e.g. joint educational opportunities).

Guided by the wider literature, we identified four stages of the coffee supply chain - cultivation, processing, retail, and consumption - and mapped opportunities for targeted interventions at each stage, linking them to the MCH (Supplementary Information S4.1 Fig. S8)[53,54]. Pressure profiles differed across early stages. While land use was primarily associated with cultivation, water consumption was more closely linked to processing due to wet milling and washing activities[55,56]. Freshwater eutrophication and climate change pressures were evident across both stages. This differentiation helps identify where efforts might be most effective. For example, East Africa's large land use component (Fig. 3) indicates that cultivation-focused interventions may yield substantial benefits. More broadly, these results suggest that action prioritisation depends on a combination of supply chain stage, regional pressure composition, and position within the MCH. Midpoint LCIA profiles can therefore inform the targeting of interventions across supply chain stages, geographies and MCH steps, while recognising inherent methodological uncertainties[22,31].

Scenario Analysis: A Sustainable Coffee Transition in Kenya

To demonstrate how the generalised workflow (Fig. 1) can be operationalised, we developed an illustrative scenario using a sourcing region (East Africa) paired with an existing research collaboration for coffee (Supplementary Information S4.3 Fig. S10). Although neighbouring Burundi was the East African sourcing location identified from limited supplier data, Kenya was selected because it hosts the largest cluster of Oxford's biodiversity and conservation partnerships and has midpoint characterisation factors available for most relevant pressures[47]. Kenya also offers a more tractable context for intervention design: all coffee growers must be formally registered, with smallholders predominantly organised through cooperatives, facilitating traceability and coordinated mitigation[57,58]. In addition, Kenya is strengthening national traceability systems to comply with the European Union's Deforestation Regulation (EUDR) and is among the few African producer countries with a coordinated compliance framework linking regulators, cooperatives, and exporters, further increasing the feasibility for supply chain mitigation and conservation action[59].

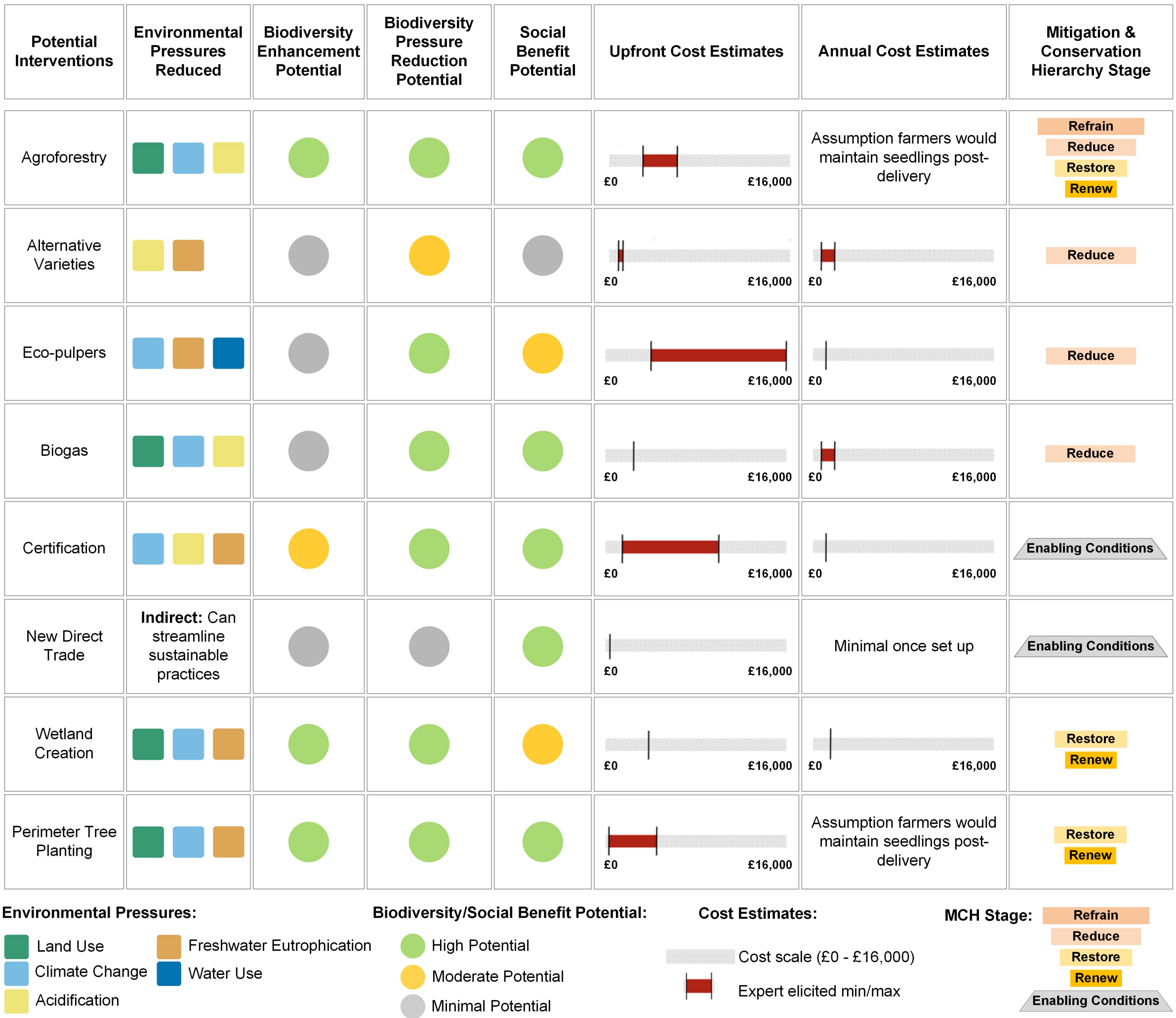
The illustrative scenario maintained the University of Oxford's annual procurement volume (3,468 kg yr^{-1}) but recalculated the associated biodiversity footprint under a hypothetical sourcing assumption where all coffee was sourced from Kenya. Under this sourcing assumption, the recalculated biodiversity footprint was 4.14×10^{-9} PDF·year, driven predominantly by land use pressures (81%), followed by eutrophication (14%) and greenhouse-gas emissions (5%), with negligible contributions from acidification and water use.

Oxford- and Kenya-based researchers co-developed impact mitigation options, first, drawing on academic and grey literature to identify promising approaches, informed by in-country knowledge of coffee production processes, cultural context, and implementation realities. Through repeated rounds of discussion, we proposed, refined, and assessed potential mitigation actions, converging on an intervention list that was evidence-informed and feasible within the local context. We prioritised mitigation actions capable of addressing multiple pressures while also delivering biodiversity, social, and research partnership co-benefits. This was in line with the University's Environmental Sustainable Strategy, with its mission of developing global, equitable partnerships and ambition to contribute to a nature positive societal goal[60].

The process highlighted the need for mitigation pathways tailored to both buyer and sourcing context. Key considerations included the level of buyer commitment, budget constraints, and feasibility of implementation, informed by multiple criteria including effectiveness, costs, stakeholder acceptability, and technical or practical considerations. Options for ongoing monitoring were also important for the decision-making process (Supplementary Information S4.2 Fig. S9). Robust monitoring is essential to determine whether planned interventions deliver intended biodiversity outcomes and to document evidence of their effectiveness over time, particularly where impacts occur in landscapes distant from the actor, such as in complex and spatially heterogeneous supply chains[61].

Across the interventions assessed, agroforestry showed the strongest combined potential for pressure reduction, biodiversity enhancement and social benefit[62-65]. Agroforestry also fell toward the lower end of expert-elicited cost ranges, both upfront and annually, and was applicable across all stages of the MCH (Fig. 5). Perimeter tree planting and wetland creation also offered large potential impact mitigation benefits, though aligned with the later MCH stages ("restore" and "renew"), and so would follow - or supplement - actions at earlier stages of the hierarchy. Other interventions offered more specific benefits: alternative coffee varieties reduced disease risk, which is increasing under climate change, while eco-pulpers and biogas systems improved water and energy efficiency[66-68]. Certification and direct trade arrangements acted primarily as enabling conditions, strengthening training, governance, and market stability rather than directly reducing pressures[69,70].

Fig. 5: Potential interventions in Kenyan coffee supply chains



Potential Interventions	Environmental Pressures Reduced	Biodiversity Enhancement Potential	Biodiversity Pressure Reduction Potential	Social Benefit Potential	Upfront Cost Estimates	Annual Cost Estimates	Mitigation & Conservation Hierarchy Stage
Agroforestry	🟩 🟦 🟨	🟢	🟢	🟢	£0 £16,000	Assumption farmers would maintain seedlings post-delivery	Refrain Reduce Restore Renew
Alternative Varieties	🟨 🟧	⚪	🟡	⚪	£0 £16,000	£0 £16,000	Reduce
Eco-pulpers	🟦 🟧 ■	⚪	🟢	🟡	£0 £16,000	£0 £16,000	Reduce
Biogas	🟩 🟦 🟨	⚪	🟢	🟢	£0 £16,000	£0 £16,000	Reduce
Certification	🟦 🟨 🟧	🟡	🟢	🟢	£0 £16,000	£0 £16,000	Enabling Conditions
New Direct Trade	**Indirect:** Can streamline sustainable practices	⚪	⚪	🟢	£0 £16,000	Minimal once set up	Enabling Conditions
Wetland Creation	🟩 🟦 🟧	🟢	🟢	🟡	£0 £16,000	£0 £16,000	Restore Renew
Perimeter Tree Planting	🟩 🟦 🟧	🟢	🟢	🟢	£0 £16,000	Assumption farmers would maintain seedlings post-delivery	Restore Renew

Environmental Pressures:
🟩 Land Use
🟦 Climate Change
🟨 Acidification
🟧 Freshwater Eutrophication
■ Water Use

Biodiversity/Social Benefit Potential:
🟢 High Potential
🟡 Moderate Potential
⚪ Minimal Potential

Cost Estimates:
▭ Cost scale (£0 - £16,000)
▬ Expert elicited min/max

MCH Stage: Refrain, Reduce, Restore, Renew, Enabling Conditions

Figure 5: Traffic-light circles denote the estimated potential - high (green), moderate (orange), or minimal (grey) - for biodiversity enhancement, biodiversity pressure reduction and social or farmer benefits, based on scoring of scalability, directness, and feasibility. Cost ranges show expert-elicited minimum and maximum upfront or annual expenses, reflecting typical project

experience and are intended as indicative rather than exhaustive. Combined interventions may generate synergistic benefits. Mitigation and Conservation Hierarchy stages follow standard definitions, and enabling conditions denote supporting actions rather than direct biodiversity measures.

Cost estimates often carry substantial uncertainty, and environmental project budgets are frequently characterised by systematic underestimation[71,72]. To contextualise intervention rankings, we therefore present expert-elicited cost ranges, noting that approximate values can still support conservation planning when transparently reported and interpreted within bounded scenarios (Fig. 5) [73].

Final Scenario Design

To illustrate how our findings could inform procurement decisions at a granular level, we developed a single scenario to represent a potential on-the-ground implementation of supply chain mitigation action for coffee. We chose Mount Elgon, Kenya, as a hypothetical smallholder production region due to its potential for collaborative engagement, through longstanding research partnerships with Oxford [57]. Drawing on the Kenya-based co-authors' in-country research experience and collective knowledge of regional coffee supply chains, we estimated that supplying approximately 3,400 kg yr^{-1} would involve around 20–50 smallholders, typically operating within cooperative structures, and as Oxford's current supply is Rainforest Alliance (RFA) certified, the scenario assumes this certification as a baseline.

The resulting scenario combines three complementary, low to medium-cost interventions selected for their pressure-reduction potential, biodiversity benefits, social outcomes and cost-effectiveness within the sourcing and organisational constraints outlined above. Based on the ranking results, agroforestry was selected as the core measure because it demonstrated the strongest combined ecological and social performance, directly addressed land use impacts, and can provide visible, trackable progress through the establishment and growth of newly planted trees (Fig. 5).

While not all shade-grown coffee systems inherently support biodiversity, a substantial body of evidence indicates that agroforestry practices incorporating native tree species can enhance habitat complexity, support a wide range of taxa, and promote resilience to the effects of climate change[74-77, 62]. Such systems have been shown to maintain or increase coffee yields.

However, biodiversity and production outcomes of agroforestry are mediated by management intensity and structural complexity. Intensified systems characterised by simplified canopies and higher agrochemical inputs are consistently associated with biodiversity loss, whereas low-intensity, structurally complex agroforestry systems enhance biodiversity, ecosystem service provision, and coffee plant health[78-80]. To mitigate the risk of yield reductions translating into unintended land use expansion, and to realise the biodiversity benefits of coffee agroforestry, such systems should be accompanied by yield monitoring and organisational-level demand moderation.

Strengthening certification practices could be a pragmatic supplementary intervention, building on Oxford's existing baseline of purchasing Rainforest Alliance (RFA) certified coffee. Certification is a widely used enabling mechanism for coffee, with potential to support improved agrochemical and water management, strengthen cooperative governance and provide structured systems for farmer training and transparent monitoring of certification-linked income premiums[69]. Certification also complements agroforestry systems, as increased shade cover can help meet criteria used in “bird-friendly” certification schemes[81].

However, certification has not consistently delivered biodiversity or production gains, highlighting the importance of strengthening scheme design and implementation to better deliver durable ecological and livelihood outcomes[69]. In particular, higher rates of uptake among higher-income households suggest a need to pair certification with targeted support mechanisms that improve accessibility and equity, potentially delivered through these intervention projects implemented with in-country partners. Alternatives to conventional certification therefore also present an avenue for further investigation. Participatory Guarantee Systems, for example, provide community-led verification and low-cost assurance, and may address well-documented limitations of standard third-party certification schemes. Exploring such systems also creates opportunities for collaborative research on their social and ecological outcomes, to support more sustainable and transparent supply chains[82].

The facilitation of direct-trade relationships was selected as a further option for low-cost action to improve price stability and market access for cooperatives, thereby supporting farmer income security and strengthening the conditions required for sustained ecological practice[54]. Direct trade relationships could also bring in a wider network (e.g. of other coffee-purchasing universities), thereby supporting systemic change within the sector.

Together, these measures formed the most effective set within the expert-elicited cost range (£4.90k-16.4k for combined up-front costs, and £0.76k-1.90k for combined annual costs), allowing for wider farmer engagement and earlier observable outcomes than higher-cost technological alternatives. We did not attempt to calculate the potential biodiversity gain from this scenario and compare it directly to the estimated biodiversity impact of Oxford's coffee purchases, as this would be comparing two highly uncertain incommensurate measures, neither of which has a robust evidence base. However, by concentrating supply of this product into a specific location and engaging with partners on the ground to implement and monitor the biodiversity impacts, this scenario would enable such analyses to be carried out in future.

These proposed mitigation actions are not supposed to be exhaustive; indeed, additional measures - such as perimeter tree planting, wetland restoration, eco-pulpers or biogas systems

- were also identified as potential mitigation options (see Supplementary S4.4). These actions would typically require greater upfront investment, higher levels of coordination, or additional infrastructure than the options assessed here, reducing their near-term feasibility. It is also critical to note that this analysis assumes that Oxford's coffee purchases remain at current levels. Demand-side or "refrain" options aimed at influencing consumption patterns within Oxford introduces additional complexity, for example through potential leakage effects (e.g. consumers purchasing coffee elsewhere), or substitution towards other beverages that have their own biodiversity footprints[83].

Discussion

Across the procurement network of a large organisation, we identify a pronounced loss of traceability and transparency that prevents determination of the origin and composition of many products. Yet, using coffee as a case study, we show that once quantity and sourcing information become available, raw materials can be linked to production regions with distinct biodiversity pressure profiles, helping identify partners for mitigation and conservation action. This approach could be scaled to address other material impacts and highlights existing collaborations as a practical means to begin addressing supply chain impacts.

However, scalability beyond products with simple supply chains and well-understood biodiversity impacts is limited. While commodities such as agricultural or timber products have comparatively well-characterised, spatially explicit pressure pathways - particularly via land occupation and transformation - this becomes more challenging for goods with greater supply chain complexity[36-38]. These constraints reflect broader limitations in inventory-level data within LCA, where complex and opaque supply chains contribute to truncation and completeness issues [14-16]. Additional barriers stem from remaining uncertainties in biodiversity characterisation models within LCIA, particularly where pressures are diffuse and spatial resolution is limited[31].

Our findings suggest that stronger procurement practices are needed to incentivise collection or sharing of biodiversity-relevant supply chain data. Addressing these challenges will require clearer reporting expectations, standardised data sharing templates, and improved supplier engagement. However, institutional reforms alone are insufficient. While carbon reporting benefits from established standards and regulations, biodiversity reporting remains largely voluntary, resulting in limited motivation for suppliers to provide biodiversity-relevant data[84-87]. This is further compounded by a lack of clear guidance on how responsibility for biodiversity impacts should be allocated across supply chain actors, including whether purchasing organisations are accountable for embedded impacts or whether responsibility should be shared among producers, intermediaries, and end users[16].

The importance of sourcing and raw material information is demonstrated through the regional variation found in Oxford's coffee footprint; both in magnitude of impact and composition of environmental pressures. Mitigation strategies must therefore be tailored to sourcing geographies[30,31]. In our coffee case study, for instance, the dominance of land use pressures in East Africa indicates that land use-focused efforts in this region could be particularly beneficial. More broadly, integrating spatially explicit LCIA outputs (Fig. 2) with our mitigation and conservation matrix (Supplementary Information S4.1 Fig.S8) illustrates how footprinting can support context-appropriate intervention design.

At the same time, biodiversity footprinting is subject to uncertainties, highlighting the need to interpret LCIA outputs alongside other methods to ensure robust decision-making[36]. In particular, regionally averaged impact estimates and aggregate proxies such as material weight or expenditure - commonly used in consumption-based footprinting - means procurement substitutions towards products with lower biodiversity impacts may not be reflected in reported footprints, weakening incentives for such changes. Consequently, greater use of on-the-ground data to monitor biodiversity responses to interventions has the potential to substantially improve estimates of impact mitigation outcomes.

This need for location-specific action emphasises an underused opportunity for universities. For Oxford, existing collaborations span all inhabited continents and frequently overlap with regions implicated in its supply chain impacts, offering trusted, on-the-ground connections with farmers, cooperatives, NGOs, and researchers. Importantly, merging mitigation action with pre-existing collaborations allows universities to align environmental sustainability strategies with other elements of their mission, including global influence and equitable research partnerships[60]. In this sense, universities are positioned not only to reduce their own biodiversity footprints and invest in compensatory actions for remaining impacts, but also to generate positive biodiversity "handprints" through learning, innovation, and diffusion of effective practices[51]. This approach is consistent with recent work emphasising the need for universities to address both on-site activities and their wider supply chain impacts, while contributing to broader shifts in how organisations engage with nature across global value chains[30,52].

The Kenya case study illustrates how such collaborations can work in practice for a single product and sourcing region (Fig. 1; Supplementary Information S4.3 Fig. S10). We demonstrated how integrating biophysical pressures, social outcomes, collaborative opportunities, and cost constraints could produce an actionable and context-appropriate intervention scenario. Empirical tests of such scenarios would help evaluate their real-world effectiveness and refine organisational approaches to supply chain mitigation. Finally, there is substantial potential for collaborative action among universities, including coordination and partnership between purchasing institutions and those located in impact regions, to drive systemic change at scale.

Altogether, this study presents a scalable approach that moves beyond recognising supply chain complexity toward enabling targeted biodiversity mitigation and conservation using practical, context-appropriate actions. By combining bottom-up traceability assessment, location-specific footprinting and adaptable implementation pathways, we bring to life a workflow for applying the MCH to organisational supply chain impacts. While our case study example of coffee is only one high-impact part of Oxford's supply chain, we believe the approach could be scaled to other material impacts that organisations have on biodiversity - helping to bring an organisation's value chain impacts into a credible Nature Positive-aligned strategy capable of delivering transformative change[34].

Methods

Supply chain assessment

We focused on three procurement categories - research, operations and construction - associated with supply chain activities that together account for most of the University of Oxford's biodiversity footprint (Supplementary Information S1.2)[7]. Supplier and products were derived from Oxford's Environmental Profit and Loss (EP&L) dataset, which quantifies environmental impacts associated with university activities, and from item-level procurement data provided by the Oxford Purchasing Department (OUP) for the 2022/23 financial year (Supplementary Information S1.3).

All subcategories within research and construction were included. For operations, the five highest-spend subcategories were selected because analysing all 29 was not feasible (Supplementary Information S1.4 & S1.5). Within each subcategory, we identified the ten highest-spend suppliers and their top three products, excluding miscoded or non-physical items, and manually cross-checking to verify product identity. In total, 131 suppliers were included: 50 from research and operations (ten in each of five subcategories), and 31 from construction, with a reduced sample for the "Flooring" subcategory owing to a limited number of physical commodities within the subcategory (Supplementary Information S1.6).

Traceability and transparency were assessed via a structured email request (with several subsequent follow-ups) to each supplier for: (a) raw materials used in products, (b) sourcing locations, and (c) availability of Life Cycle Assessment (LCA) data (Supplementary Information S1.7). For each supplier, we recorded whether they responded, whether information was provided, and the stated rationale for non-disclosure when applicable. Suppliers were classified as distributors (entities reselling goods manufactured by others) or manufacturers to characterise vertical complexity[39]. For distributors, we also recorded whether they were willing to contact upstream suppliers, providing an indicator of transparency beyond the first tier.

Tracing and estimating biodiversity impacts

Invoices within the research, operations and construction categories reported financial expenditure only, aggregated across multiple suppliers. As spend does not consistently reflect material quantity, we used a separate category, food procurement, where both quantity and weight were available, to demonstrate how organisations can trace the origins of a raw commodity and estimate associated biodiversity impacts (Supplementary Information S2).

Food procurement data for University of Oxford cafeterias was provided by Compass Group plc, which supplies 19 cafeterias across Oxford. Transaction records were extracted from the company's internal procurement platform for 1 August 2022 to 31 July 2023. As nine additional cafeterias are supplied by other contractors, total consumption was extrapolated to university level (Supplementary Information S2.1).

Coffee was selected as the focal product because it is procured in raw material form, reducing supply chain complexity relative to compound products, and because, despite representing a small percentage of the University of Oxford's overall footprint (see Bull et al., 2022 Supplementary Information), it is a high-impact commodity for which complete elimination is neither feasible nor socially desirable[22,71,74] Continued procurement is necessary to meet university demand (otherwise significant demand leakage to other outlets is likely), and to support livelihoods in producing regions, where coffee contributes significantly to GDP and employment[43-45].

Coffee data was filtered to include roast, ground, and whole bean, with the total mass purchased calculated by multiplying pack size (weight per pack) by the invoice quantity. Communication with Compass confirmed that “Change Please Coffee” supplies Oxford’s cafeterias, and sources from five countries: Columbia, Peru, Brazil, Honduras, and Burundi.

Biodiversity impacts were estimated using the LC-IMPACT Life Cycle Impact Assessment (LCIA) framework, an extension of Life Cycle Assessment (LCA) methodologies providing regionally specific endpoint biodiversity impact characterisation factors (CFs) and therefore offering greater spatial resolution than alternative LCIA models such as ReCiPe[32,33,46]. Whilst several LCIA frameworks exist, each varying in their assumptions and CFs, relative comparisons among sourcing regions remain robust when a consistent framework is applied.

Country-level midpoint environmental impact CFs were obtained from Poore & Nemecek (2018), a global LCA meta-analysis of many agricultural products, including coffee, and spanning multiple environmental impact categories (Supplementary Information S2.2)[47.] To reflect sourcing locations while accommodating data gaps, biodiversity footprint calculations were conducted at a regional level (South America, Central America, and East Africa). Midpoint environmental impact CFs were unavailable for three of the five sourcing countries (Burundi, Honduras, and Peru) and for two environmental impact categories (acidification and freshwater eutrophication) in Colombia. Kenya was the only country with complete CFs in East Africa and was therefore used as a regional proxy, and missing Kenyan CFs for freshwater eutrophication and acidification were substituted with global averages. To enable direct comparison of different environmental impact profiles and total biodiversity footprints across regions in the absence of sourcing quantities, the total coffee mass was divided equally among the three regions.

LC-IMPACT expresses biodiversity loss as “Potentially Disappeared Fraction of species” within a year (PDF.year), representing the fraction of species facing increased risk of irreversible global extinction over time[46]. Where necessary, multipliers from an alternative model ReCiPe were used to convert midpoint environmental pressures into endpoint compatible units, such as conversion of PO_4 to P equivalents (Supplementary Information S2.1)[32]. Sensitivity analyses using ReCiPe and global CFs, and Spearman rank tests for consistency in pressure hierarchies, are provided in the Supplementary Information S2.3.

Developing mitigation strategies

Supply chain mitigation and conservation opportunities were identified by mapping Oxford's global biodiversity and conservation research collaborations. A survey containing up to 15 questions per collaboration was distributed to relevant Oxford researchers, who could submit up to five collaborations each (Supplementary Information S3). Respondents reported collaboration locations, partner institutions, research strength, and whether collaborations could contribute to addressing supply chain impacts. A dedicated section focused on coffee to identify linkages in producing regions. Where multiple respondents reported collaborations in the same country, the country was coded as having mitigation potential if at least one respondent answered 'yes' (Fig. 4b).

Scenario development: sustainable coffee transition in Kenya

We conducted a non-systematic literature review to identify key stages of the coffee supply chain and combined these with survey findings to develop a matrix of potential interventions aligned with the Mitigation and Conservation Hierarchy (Supplementary Information S4.1 Fig. S8). LCIA results and literature were used to identify dominant environmental pressures at cultivation and processing stages.

We selected Mount Elgon, Kenya as the hypothetical production region because Kenya hosts Oxford's largest cluster of biodiversity and conservation research activities, and midpoint characterisation factors for East African coffee in Poore & Nemecek (2018) are derived from Kenyan LCA[47]. Kenya also provides a more operationally feasible context for coordinated supply chain mitigation due to its formal grower registration, cooperative-dominated smallholder system, and strengthening EUDR-aligned traceability framework[57-59].

A practical mitigation and conservation scenario was co-developed through two workshops involving researchers from Strathmore University (Kenya) and Oxford University and two Kenyan agronomists (all of whom are co-authors of this paper). The objective was to maintain Oxford's annual procurement volume (3,468 kg yr^{-1}) while reducing environmental pressures and generating social and research co-benefits. The objective was not to produce enough biodiversity gain to compensate fully for negative impacts, as this would require gains and losses to be specified in comparable units. That said, this could be done in future as on-the-ground actions and associated monitoring programmes are implemented.

Before the first workshop, midpoint pressures were recalculated assuming all coffee was sourced from Kenya. Intervention goals were defined for each impact category (e.g., land restoration for land-use impacts; nutrient management for eutrophication) and candidate measures were drawn from the literature-derived intervention matrix for evaluation by Kenyan co-authors (Supplementary Information S4.1 Fig. S8).

During the first workshop, the participants identified the pressures addressed by each intervention. Using information collected during the first workshop, interventions were assessed using a structured qualitative process across three dimensions: biodiversity enhancement, pressure reduction, and social benefit. Each dimension was then evaluated using three predefined criteria: (1) scalability, defined as the potential to expand the interventions ; (2) directness of impact, defined as the degree to which an intervention provides direct outcomes through immediate and causal pathways; and (3) feasibility, defined as how practically achievable the intervention is to deliver these dimensions, within the local context. Each criterion was scored on a three-point ordinal scale (1-3). Criterion scores were aggregated using an unweighted mean to generate a composite score for each dimension, which was then translated into a categorical "traffic-light" rating of high (≥2.5), moderate (1.5–2.4) or minimal (<1.5) impact.

Preliminary scores were presented and discussed during the second workshop, where participants reviewed and refined the assessments. Following a facilitated discussion, final categorical ratings were agreed upon. Approximate intervention costs were discussed with the participating agronomists, who provided indicative minimum and maximum cost estimates for each intervention based on experience with comparable projects in the region.

Costs were classified as either upfront or annual. These results were used to construct a final hypothetical scenario during the second workshop, including the target region and number of farmers, a proposed core set of interventions, long-term extension options, research monitoring pathways through Strathmore University and estimated costs. This process also produced a transferable decision framework outlining sequential steps for developing tailored supply chain mitigation scenarios, including defining scope and sourcing geography, buyer commitment and budget, and options for monitoring and tracking progress (Supplementary Information S4.2 Fig. S9).

References

1. World Economic Forum. Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy. (WEF, 2020).

2. Taskforce on Nature-related Financial Disclosures. *TNFD.* Available at: https://tnfd.global/ (2020).

3. zu Ermgassen, S. O. S. E. *et al.* Are corporate biodiversity commitments consistent with delivering 'nature-positive' outcomes? A review of 'nature-positive' definitions, company progress and challenges. *J. Clean.Prod.* **379**, 134798 (2022).

4. World Wildlife Fund. *2024 Living Planet Report: A System in Peril*. (WWF, 2024).

5. Convention on Biological Diversity. COP15: Final text of Kunming-Montreal Global Biodiversity Framework available in all UN languages. *Convention on Biological Diversity* (2022). https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222

6. Lenzen, M. *et al.* International trade drives biodiversity threats in developing nations. *Nature* **486**, 109–112 (2012).

7. Bull, J. W. *et al.* Analysis: the biodiversity footprint of the University of Oxford. *Nature* **604**, 420–424 (2022).

8. Berger, J., Goedkoop, M. J., Broer, W., Nozeman, R., Grosscurt, C. D., Bertram, M. & Cachia, F. *Common ground in biodiversity footprint methodologies for the financial sector.* Paris (2018).

9. Kering. *Environmental Profit & Loss (EP&L) results.* https://www.kering.com/en/sustainability/measuring-our-impact/our-ep-l/ep-and-l-results/ (2024).

10. Puma. *Clever Little Report*. https://about.puma.com/sites/default/files/financial-report/2011/ar-2011.pdf (2011).

11. Thurston, M. & Eckelman, M. J. Assessing greenhouse gas emissions from university purchases. *Int. J. Sustain. High. Educ.* **12**, 225–235 (2011).

12. Nature Positive Initiative. *Nature Positive Initative* https://www.naturepositive.org/ (2023).

13. Sodhi, M. S. & Tang, C. S. Research opportunities in supply chain transparency. *Prod. Oper. Manag.* **28**, 2946–2959 (2019).

14. Grimard, A., Lake, S., Mardas, N., Godar, J. & Gardner, T. A. *Supply chain transparency network: State of play.* Supply Chain Transparency Network (2017).

15. Schaëfer, K., Kähkönen, A.-K. & Luzzini, D. Traceability in multi-tier supply chains: insights from five case studies. *Supply Chain Manag.* **30**, 77–99 (2025).

16. Gardner, T. A. Transparency and sustainability in global commodity supply chains. *World Dev.* **121**, 163–177 (2019).

17. Gualandris, J., Longoni, A., Luzzini, D. & Pagell, M. The association between supply chain structure and transparency: A large-scale empirical study. *J. Oper. Manag.* **67**, 803–827 (2021).

18. TRASE. *Trase.* https://trase.earth/. (2024).

19. Kurth, T. *et al. The biodiversity crisis is a business crisis.* Boston Consulting Group & World Wildlife Fund https://web-assets.bcg.com/fb/5e/74af5531468e9c1d4dd5c9fc0bd7/bcg-the-biodiversity-crisis-is-a-business-crisis-mar-2021-rr.pdf (2021).

20. West, C., Titley, M., Croft, S., Molotoks, A., Simpson, J. & Green, J. *Assessing tropical deforestation and biodiversity risk in Belgium's agricultural commodity supply chains.* Trase/Stockholm Environment Institute (2022).

21. Maron, M. *et al.* 'Nature positive' must incorporate, not undermine, the mitigation hierarchy. *Nat. Ecol. Evol.* **8**, 14–17 (2024).

22. Science Based Targets Network (SBTN). *Science Based Targets Network* https://sciencebasedtargetsnetwork.org/ (2023).

23. André, H., Ljunggren Söderman, M. & Nordelöf, A. Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. *Waste Manag.* **88**, 268–279 (2019).

24. Khan, A. R. Transforming electronics lifecycle through expert refurbishment, quality assurance, and transparent environmental impact. *Res. Corridor J. Eng. Sci.* **2**, 58–72 (2025).

25. Trusler, E. C., Davies, M., Spurrier, B. & Gould, S. J. Reusable glassware for routine cell culture—a sterile, sustainable and affordable alternative to single-use plastics.

Front. Sustain. **5**, (2024).

26. Amaro, A., Pillay, S. & Grosscurt, C. *Utrecht University Biodiversity Footprint 2024: Materiality assessment, footprint and scenario analysis.* Utrecht University (2024).

27. OECD. *Scaling Up Biodiversity-Positive Incentives: Delivering on Target 18 of the Global Biodiversity Framework.* OECD Publishing (2025). https://doi.org/10.1787/19b859ce-en

28. Baggaley, S. *et al. Nature positive for business*. IUCN (2023). https://portals.iucn.org/

29. Bang, A. *et al. A typology of corporate actions for a nature-positive future.* EcoEvoRxiv (2025). https://ecoevorxiv.org/repository/view/10429/

30. Schlecht, V. *et al.* From local species monitoring to global value chain impacts: A starting point for assessing biodiversity impacts of higher education institutions. *Biol. Conserv.* **313**, 111613 (2025).

31. Bromwich, T. *et al.* Navigating uncertainty in life cycle assessment-based approaches to biodiversity footprinting. *Methods. Ecol. Evol.* 1–18 (2025)

32. Huijbregts, M. A. J. *et al.* ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **22**, 138–147 (2016).

33. Hellweg, S., Benetto, E., Verones, F. & Wood, R. Life-cycle assessment to guide solutions for the triple planetary crisis. *Nat. Rev. Earth Environ.* **4**, 471–486 (2023).

34. Booth, H., Milner-Gulland, E. J., McCormick, N. & Starkey, M. Operationalizing transformative change for business in the context of Nature Positive. *One Earth* **7** (2024).

35. Milner-Gulland, E. J. *et al.* Four steps for the Earth: mainstreaming the post-2020 global biodiversity framework. *One Earth* **4**, 75–87 (2021).

36. Crenna, E., Marques, A., La Notte, A. & Sala, S. Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. *Environ. Sci. Technol.* **54**, 9715–9728 (2020).

37. Bode, C. & Wagner, S. M. Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. *J. Oper. Manag.* **36**, 215–228 (2018).

38. Choi, T. Y. & Hong, Y. Unveiling the structure of supply networks: case studies in Honda, Acura, and DaimlerChrysler. *J. Oper. Manag.* **20**, 469–493 (2002).

39. Smith, P. M., Ross, E. S. & Smith, T. A case study of distributor-supplier business relationships. *J. Bus. Res.* **39**, 39–44 (1997).

40. Kembro, J., Näslund, D. & Olhager, J. Information sharing across multiple supply chain tiers: a Delphi study on antecedents. *Int. J. Prod. Econ.* **193**, 77–86 (2017).

41. Garcia-Torres, S., Rey-Garcia, M. & Sáenz, J. Enhancing sustainable supply chains through traceability, transparency and stakeholder collaboration: a quantitative analysis. *Bus. Strateg. Environ.* **33** (2024).

42. Ball, T.S., Dales, M., Eyres, A. et al. Food impacts on species extinction risks can vary by three orders of magnitude. *Nat Food* **6**, 848–856 (2025).

43. Treanor, N. & Saunders, J. Tackling (illegal) deforestation in coffee supply chains: What impact can demand-side regulations have? Forest Trends (2021). Available at: https://www.forest-trends.org/publications/tackling-illegal-deforestation-in-coffee-supply-chains-what-impact-can-demand-side-regulations-have/

44. Fairtrade Foundation. *Coffee farmers.* Fairtrade Foundation (2021). https://www.fairtrade.org.uk/farmers-and-workers/coffee/

45. Karuri, A. N. Adaptation of Small-Scale Tea and Coffee Farmers in Kenya to Climate Change. in *African Handbook of Climate Change Adaptation* 1–19 (Springer, 2020). https://doi.org/10.1007/978-3-030-42091-8_70-1.

46. Verones, F. *et al.* LC-IMPACT: A regionalized life cycle damage assessment method . *J. Ind. Ecol.* **24**, 1201–1219 (2020).

47. Poore, J. & Nemecek, T. Reducing Food's Environmental Impacts through Producers and Consumers. *Science* **360**, 987–992 (2018).

48. Godar, J., Persson, U. M., Tizado, E. J. & Meyfroidt, P. Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption. *Ecol. Econ.* **112**, 25–35 (2015).

49. Usva, K., Sinkko, T., Silvenius, F., Riipi, I. & Heusala, H. Carbon and water footprint of coffee consumed in Finland—life cycle assessment. Int. J. Life Cycle Assess. **25** (2020).

50. Hauschild, M. Z., Rosenbaum, R. K. & Olsen, S. I. *Life Cycle Assessment*. (Springer International Publishing, 2018). https://doi.org/10.1007/978-3-319-56475-3.

51. Sandström, V., Kauppi, P. E., Scherer, L. & Kastner, T. Linking country level food supply to global land and water use and biodiversity impacts: The case of Finland. *Sci. Total Environ.* **575**, 33–40 (2017).

52. Alvarenga, R. A. F. *et al.* A framework for using the handprint concept in attributional life cycle (sustainability) assessment. *J. Clean. Prod.* **265**, 121743 (2020).

53. De Felice, F., Rehman, M., Petrillo, A. & Baffo, I. Decoding the coffee supply chain: A systematic review of stakeholders, sustainability opportunities, and challenges. *Sustain. Fut.* **10**, 101105 (2025).

54. LiangHui, D. & Reeveerakul, N. Analysis of Critical Knowledge in a Coffee Supply Chain. In *2019 Joint International Conference on Digital Arts, Media and Technology with ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI DAMT-NCON).* (2019). https://doi.org/10.1109/ecti-ncon.2019.8692290.

55. Adams, M. & Ghaly, A. E. Maximizing sustainability of the Costa Rican coffee industry. *J. Clean. Prod.* **15**, 1716–1729 (2007).

56. Robbins, P., Tripuraneni, V., Karanth, K. K. & Chhatre, A. Coffee, trees, and labor: Political economy of biodiversity in commodity agroforests. *Ann. Am. Assoc. Geogr.* **111**, 1046–1061 (2020).

57. Wambua, D. M., Ndirangu, S. N., Mogaka, H. & Gichimu, B. M. Determinants of the produced coffee volumes and choice of marketing channels among smallholder coffee farmers in Embu and Kirinyaga counties, Kenya. *Humanit. Soc Sci. Commun.* **12**, (2025).

58. Government of Kenya. *The Crops (Coffee) (General) Regulations*. *Kenyalaw.org* vol. Legal Notice No. 102 of 2019 (2019).

59. TradeMark Africa. *Kenya Strengthens Traceability to Meet Deforestation-Free Market Standards.* Trademarkafrica.com (2025). https://trademarkafrica.com/kenya-strengthens-traceability-to-meet-deforestation-free-market-standards/

60. University of Oxford. *Environmental Sustainability Strategy.* sustainability.admin.ox.ac.uk (2021). https://sustainability.admin.ox.ac.uk/environmental-sustainability-strategy

61. Henry, P.-Y. *et al.* Integrating ongoing biodiversity monitoring: potential benefits and methods. *Biodivers. Conserv.* **17**, 3357–3382 (2008).

62. Tscharntke, T. *et al.* Multifunctional shade-tree management in tropical agroforestry landscapes - a review. *J. Appl. Ecol.* **48**, 619–629 (2011).

63. Ramni Jamnadass, Place, F., Torquebiau, E. & Dawson, I. Agroforestry, food and nutritional security. *ResearchGate* (2013). https://www.researchgate.net/publication/254864845_Agroforestry_food_and_nutritional_security

64. Lehmann, L. M. *et al.* Productivity and economic evaluation of agroforestry systems for sustainable production of food and non-food products. *Sustainability* **12**, 5429 (2020).

65. Jung, D. R. & Vendrametto, O. Agroforestry for food security and public health: A comprehensive review. *Int. J. Environ. Res. Public Health* **22**, 645 (2025).

66. Duque-Dussán, E., Sanz-Uribe, J. R., Dussán-Lubert, C. & Banout, J. Thermophysical properties of parchment coffee: New Colombian varieties. . *Food Process Eng.* (2023). https://doi.org/10.1111/jfpe.14300.

67. Kipkorir, R. K., Muliro, P. & Muhoho, S. Effects of coffee processing technologies on physico-chemical properties and sensory qualities of coffee. *Afr. J. Food Sci.* **9**, 230–236 (2015).

68. Wariyo, A., Dejene, M. & Derso, E. Reaction of Southern coffee germplasms to coffee berry disease (*Colletotrichum kahawae* Waller and Bridge), in Southern Ethiopia. *Bioprocess Eng.* **9**, 58–69 (2025).

69. Bray, J. G. & Neilson, J. Reviewing the impacts of coffee certification programmes on smallholder livelihoods. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **13**, 216–232 (2017).

70. Kamau, M., Mose, L. & Fort, R. *The Impact of Certification on Smallholder Coffee Farmers in Kenya: The case of 'UTZ' certification program* (2010). https://www.enterprise-development.org/wp-content/uploads/Kamau-Impact-of-Certification-in-Kenya-2010.pdf

71. White, T. B., Petrovan, S. O., Christie, A. P., Martin, P. A. & Sutherland, W. J. What is the price of conservation? A review of the status quo and recommendations for improving cost reporting. *BioScience* **72**, (2022).

72. Flyvbjerg, B. & Bester, D. W. The Cost-Benefit Fallacy: Why Cost-Benefit Analysis Is Broken and How to Fix It. *Ssrn.com* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3918328 (2021).

73. Carwardine, J. et al. Conservation planning when costs are uncertain. *Conserv. Biol.* **24**, 1529–1537 (2010).

74. Wynter, V., Milner-Gulland, E. J. & Poore, J. A global comparison of the biodiversity impacts of coffee agricultural systems—From monoculture to diverse agroforestry. *Agric. Syst.* **229**, 104449 (2025).

75. Perfecto, I. & Vandermeer, J. Spatial pattern and ecological process in the coffee agroforestry system. *Ecol.* **89**, 915–920 (2008).

76. Nasiro, K. The benefits of agroforestry coffee production systems: A review. *World J. Food Sci. Technol.* **8**, 86–105 (2024).

77. De Beenhouwer, M., Aerts, R. & Honnay, O. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. *Agric. Ecosyst. Environ.* **175**, 1–7 (2013).

78. Moguel, P. & Toledo, V. M. Biodiversity conservation in traditional coffee systems of Mexico. *Conserv. Biol.* **13**, 11–21 (1999).

79. Philpott, S. M. et al. Biodiversity loss in Latin American coffee landscapes: Review of the evidence on ants, birds, and trees. *Conserv. Biol.* **22**, 1093–1105 (2008).

80. Jose, S. Agroforestry for ecosystem services and environmental benefits: An overview. *Agrofor. Syst.* **76**, 1–10 (2009).

81. Smithsonian Migratory Bird Center. Smithsonian Bird Friendly. *Smithsonian's National Zoo* https://nationalzoo.si.edu/migratory-birds/bird-friendly (2017).

82. Loconto, A. & Hatanaka, M. Participatory guarantee systems: Alternative ways of defining, measuring, and assessing 'sustainability'. *Sociol. Ruralis* **58**, 412–432 (2017).

83. Balmford, A. *et al.* Time to fix the biodiversity leak. *Science* **387**, 720–722 (2025).

84. World Resources Institute. Greenhouse Gas Protocol. *World Resources Institute* https://www.wri.org/initiatives/greenhouse-gas-protocol (2024).

85. British Universities Finance Directors Group & Higher Education Procurement Association. Embedding nature and biodiversity into higher education procurement. *BUFDG* https://www.bufdg.ac.uk/ (2023).

86. International Organization for Standardization. ISO 14064-1:2018 Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. *(International Organization for Standardization, 2018).*

87. International Organization for Standardization. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. *(International Organization for Standardization, 2006).*

Acknowledgements

T.B., T.W., and H.B. were funded by the Leverhulme Trust as part of the Leverhulme Centre for Nature Recovery, University of Oxford (RC-2021-076). E.S. was supported by the Tasso Leventis Endowment, and A.L. by the Darwin Initiative (project DIR31IN11513) and the Ardevora Foundation. E.F. was supported by the Oxford Sustainability Fund. We thank J. Poore for support with coffee LCIA estimation methods and country-level characterisation factor data.

Author Contributions

É. F., T. B., S. z. E., and E. J. M.-G. conceived the study. É. F. conducted the traceability study, with support from H. N. in navigating the university's procurement dataset, and performed the coffee biodiversity footprinting analysis, with methodological support from T. B. É. F. developed the mitigation/conservation coffee matrix in collaboration with A. K., S. T. M., and K. M. The original draft manuscript was led by É. F., with input and review from all authors.