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Supporting decision-making by companies in delivering their climate net-zero and nature recovery commitments: Synthesising current information and identifying research priorities in rainforest restoration

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A R T I C L E I N F O

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A B S T R A C T

Many companies are making ambitious pledges to achieve positive impacts for climate and nature by financing restoration of carbon- and biodiversity- rich natural habitats. However, companies cannot make evidence-based choices that will deliver successful restoration if the scientific information required to guide investment has not been synthesised in a way that they can use, or there are knowledge gaps. To explore this issue, share information, and identify knowledge gaps and research priorities, we bring together researchers, a conservation NGO and a multinational consumer goods company (Unilever), focusing on Southeast Asian rainforests. These habitats offer significant restoration opportunities for carbon and biodiversity in areas that have been degraded by commercial logging and agriculture. We find that procedures for carbon restoration are much better developed than those for biodiversity, and that new research is urgently needed to deliver evidence-based biodiversity restoration. Companies need to be confident that their actions are fit-for-purpose to meet their environmental pledges. Achieving successful restoration outcomes will require co-designed projects with the potential to deliver positive co-benefits for carbon, biodiversity and local livelihoods.

1. Introduction: Industry pledges to restore tropical forests

Destruction of rainforests is recognised as a major driver of global biodiversity loss, reduction of ecosystem services and the release of anthropogenic greenhouse gas emissions (IPBES, 2019; IPCC (Intergovernmental Panel on Climate Change), 2013). Concerns about climate and biodiversity crises have led many companies to take decisive action to tackle climate change and conserve biodiversity

Abbreviations: APBON, Asia Pacific Biodiversity Observation Network; CFS, Central Forest Spine; COP, Conference of the Parties; HCS, High Carbon Stock; HCV, High Conservation Value; RSPO, Roundtable on Sustainable Palm Oil; SDGs, Sustainable Development Goals; WWF, World Wide Fund for Nature.

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Table 1
Examples of corporate climate and nature pledges and associated tropical forest restoration and regeneration projects with intended outcomes (note that this excludes conservation projects and examples of restoration outside of tropical forests) for multinational companies. A number of examples in this compilation table were chosen because they are a collaboration with existing Unilever projects, whilst others were selected from searching company websites, or they were case studies from One Planet Business for Biodiversity (OP2B; https://www.wbcsd.org/Projects/OP2B), or examples from1t.org (https://www 0.1 t.org/).

Company	Corporate commitment	Mechanism	Tropical forest restoration projects	Source
Amazon	The Climate Pledge: a commitment to be net-zero carbon across the business by 2040	Right Now Climate Fund: a $100 million fund to restore and conserve forests, wetlands, and grasslands around the world	Agroforestry and Restoration Accelerator, in the Brazilian Amazonian state of Pará in partnership with The Nature Conservancy. Intended outcomes: • Support local farmer incomes • Carbon removal Lowering Emissions by Accelerating Forest finance (LEAF) Coalition, a global initiative of governments (including Costa Rica, Ecuador, Ghana, Nepal and Vietnam) and leading companies. Intended outcomes: • Reduce emissions from deforestation and degradation • Increase carbon sequestration • Improve livelihoods	https://sustainability.aboutamazon.com/about/the-climate-pledge/nature-based-solutions https://leafcoalition.org/
Astra Zeneca	Ambition Zero Carbon commitment	'AZ Forest' restoration initiative	50 million tree reforestation initiative in partnership with local governments and One Tree Planted non-profit organisation. Intended outcomes in Kalimantan National Park, Indonesia: • 10 million trees by 2025 • Biodiversity and carbon sequestration Intended outcomes in Citarum River, Indonesia: • 10 million trees by 2025 • Erosion control and watershed protection • Biodiversity and carbon sequestration	https://www.astrazeneca.com/media-centre/articles/2020/ambition-zero-carbon-22012020.html# https://www 0.1 t.org/pledges/az-forest
Barry Callebaut	Forever Chocolate Plan: includes goal to become carbon and forest positive by 2025	Forest regeneration and protection partnerships	Reforestation and restoration project in Agbo 2, in the Moronou region, Ivory Coast, employing automated aerial planting (i.e., drone seeding and monitoring). Intended outcomes: • Replenish carbon sinks • Create employment opportunities for local communities	https://op2b.org/wp-content/uploads/2022/03/Barry-Callebaut.pdf https://www.barry-callebaut.com/en/group/forever-chocolate/sustainability-reporting/forever-chocolate-progress-report-202021

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Table 1 (*continued*)

Company	Corporate commitment	Mechanism	Tropical forest restoration projects	Source
International Paper Company	'Sustaining Forests' Commitment	WWF's Forests Forward programme	Atlantic Forest Restoration: Mogi Guaçu River basin, Brazil, partnering with WWF-US to convene a multi-stakeholder group and fund for forest restoration. Intended outcomes: • Benefits for nature, climate and people	https://www.internationalpaper.com/planet/collaborations
JDE Peet	'Common Grounds' Strategy: includes goals to reduce absolute scope 1 and 2 emissions 25% by 2030 (2020 base year) and reduce absolute value chain scope 3 greenhouse gas emissions 12.5% by 2030 (2020 base year)	Supplier engagement programme	The Bukit Barisan Selatan Sustainable Commodities Partnership (BBS KEKAL) - Wildlife Conservation Society (WCS), JDE, Nestlé , coffee suppliers, the Indonesian government, communities and civil society. Intended outcomes: • Avoid 20,000 ha of deforestation in the park as compared to business as usual • Restore 2500 ha of degraded forests	https://www.jdepeets.com/sustainability/common-grounds/ https://op2b.org/wp-content/uploads/2022/03/JDE.pdf
Kering	Deliver net-zero greenhouse gas emissions by 2050 Biodiversity Strategy	Offset programmes	Reforestation programme for former alluvial gold mining site in French Guiana covering 116 ha of the Amazon forest. Working with Solicaz and Forest Finance. Intended outcomes: • Plant 214,780 trees over 4 years • Generate carbon credits • Retore habitat and biodiversity • Carbon sequestration	https://www.kering.com/en/sustainability/mitigating-climate-change/restore-and-regenerate/ https://keringcorporate.dam.kering.com/m/5be728cdf4bcfa42/original/Kering-Biodiversity-Strategy.pdf
Nestlé	Halve greenhouse gases by 2030 and achieve net zero by 2050; including pledge to plant 200 million trees over the next 10 years	Reforestation programme	RELeaf project – Nestlé Malaysia and Yayasan Sime Darby have committed to planting three million trees in the Sabah, Malaysian Borneo. This is a CHF 4 million investment over the next 3 years. Intended outcomes: • Preserve biodiversity with wildlife corridors • Buffer zone for sediment and nutrient run-off to improve water quality • Improve livelihoods • Absorb carbon Rimba Collective – developed by Lestari Capital in collaboration with Nestlé and other founding partners,	www.nestle.com/stories/nestle-helps-save-kinabatangan-river https://lestaricapital.com/wp-content/uploads/2021/04/Rimba-Collective_Launch-Press-Release_8-April-2021.pdf

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Table 1 (*continued*)

Company	Corporate commitment	Mechanism	Tropical forest restoration projects	Source
			PepsiCo, Procter & Gamble and Wilmar. $1 billion to protect or restore 500,000 ha of forest in Southeast Asia over 25 years, starting in Indonesia. Intended outcomes: • Carbon sequestration • Water purification • Soil health • Resilient livelihoods	
PepsiCo	1.5 °C Pledge	Nature-based solutions	Sustainable Livelihoods Programme in the Aceh Tamiang district of North Sumatra, Indonesia. Intended outcomes: • Restore 300 ha of forests Rimba Collective (as above, under Nestlé)	https://www.pepsico.com/esg-topics-a-z/deforestation https://us 0.1 t.org/pledge/pepsico-and-nature-based-solutions-to-1–5c/
Shell	Become a net-zero emissions energy business by 2050	Nature-based carbon offsets	Reforestation of degraded forest reserves in Ghana. Intended outcomes: • Increase forest cover • Increase biodiversity • Improve water and soil quality • Job provision • Annual carbon credit generation Qianxinan Afforestation Project, China. Intended outcomes: • Establish forest cover on barren land • Generate greenhouse gas emission reductions (and annual carbon credits)	https://www.shell.com/energy-and-innovation/new-energies/nature-based-solutions.html#iframe=L3dlYmFwcHMvRVBUQi1OQlMtR2xvYmUv
Zurich	1.5 °C Pledge	Zurich Forest Project: grant enabling tree planting	Zurich Forest Project in the Atlantic Forest on Brazil's eastern coast - collaboration with Instituto Terra enabling one million seedlings to be planted over eight years. Intended outcomes: • Help local economy • Mitigate climate impact	https://www.zurich.com/en/about-us/sponsorship/zurich-forest/project

through their sustainability pledges. For example, in 2020, as part of its Compass Strategy, Unilever committed to invest €1bn in a new Climate and Nature fund intended for landscape restoration, reforestation, carbon sequestration, wildlife protection and water preservation projects (see Case Study 1: Corporate ambitions for restoration – The Unilever Compass). Many other organisations have made similar environmental pledges and there are increasing numbers of companies implementing forest restoration projects (Table 1 lists pledges by 10 multinational companies). Moreover, it is estimated that ~$100 billion annual funding is required to deliver on Conference of the Parties (COP) targets for biodiversity (Barbier et al., 2018), much of which is likely to come from private finance. Hence, it is imperative that restoration initiatives funded by companies are informed by robust science and any claimed benefits supported by appropriate evidence if corporate environmental pledges are to deliver for nature and climate.

If implemented appropriately, reforestation (defined as the 're-creation of forest on a previously forested area') and forest restoration ('restoration of degraded, damaged or destroyed forested areas'; definitions taken from Di Sacco et al., 2021) have been proposed as cost-effective nature-based climate solutions to tackle these climate and biodiversity problems (Brancalion et al., 2019;

Table 2
We set out five questions to support decision-making by industry, which synthesise the current scientific evidence, identify knowledge gaps and challenges, provide recommendations based on current evidence and suggest new research and knowledge generation to ensure successful forest restoration projects that return positive impacts for climate and nature. Our focus is on Southeast Asia and so we assume impacts are linked to industry carbon and nature commitments in the context of landscapes that are dominated by dipterocarp forest and oil palm plantations.

Key questions	The current scientific evidence base to support action	Recommendations based on current evidence	Current unknowns, knowledge gaps and challenges	Moving forwards: information generation
1. **What impacts are required from restoration?**	There are many opportunities to restore carbon, for which there are established protocols and metrics to quantify impacts. Opportunities and protocols for biodiversity restoration are less clear, but usually linked to carbon restoration.	Restoring carbon stocks will produce better quality forest supporting higher forest biodiversity.	Opportunities for committing to biodiversity restoration /offsetting schemes are limited. Restoration for biodiversity is currently risky because there is limited evidence on methods for quantifying impacts, especially for animal diversity and ecosystem functioning.	Develop robust metrics and monitoring for quantifying biodiversity restoration impacts to ensure verifiable benefits. Develop guidance on identifying restoration opportunities that deliver multiple impacts for carbon, biodiversity and livelihoods. Better understanding of which impacts can be optimised with minimum cost, and trade-offs.
2. **Which types of habitat will deliver the best restoration impacts?**	Regenerating current degraded forest is easier and cheaper than restoring cleared forest, and will more quickly resemble intact forest. Restoration within planted areas will benefit sustainable practices in company supply chains/sheds but may not offer sizeable contributions, or additionality, but may benefit forest connectivity and plantation permeability.	Restoring degraded forest areas will avoid displacement of agriculture and reduce potential detrimental impacts for local communities.	Unclear where and how much degraded forest is available for restoration to allow companies to meet net zero. Unclear whether restoring degraded forest will deliver sufficiently large beneficial impacts for biodiversity and carbon for investors. Unclear how carbon and biodiversity accumulate over time in respect to starting baselines (i.e., degraded forest versus cleared forest baselines) and local context, such as size and isolation of restored sites (i.e., proximity to source populations for seeds and biodiversity).	Develop guidelines and methods for high-resolution mapping of forest restoration opportunities at regional scales (e.g., maps integrating current carbon stocks, biodiversity distribution, local stakeholder needs). Improve carbon and biodiversity accumulation models for different forest types and locations.
3. **Which sites will deliver the greatest beneficial impacts?**	Many opportunities to restore highly degraded forest set-asides and riparian buffer zones, to protect ecosystem functions and provide biodiversity refuges in agricultural areas. Large forest remnants (>200 ha) support high biodiversity, and degraded sites will benefit from restoration. Small forest remnants provide stepping-stones for connectivity, which is enhanced by restoration, but very small patches can experience substantial edge effects.	Focusing restoration on large tracts of degraded forest (e.g., commercially logged production forest) will provide substantial opportunities for positive carbon and biodiversity impacts, and enhance landscape-scale connectivity.	Methods unclear on how to restore cleared areas, such as creating riparian buffer strips in plantations. Unclear how edge effects will limit restoration for carbon in small forest remnants. Unclear if restoration of riparian strips may displace agriculture elsewhere if local yields are reduced.	Develop guidance for restoring areas of cleared forest and agricultural areas. Develop guidelines on the minimum area of forest that can be successfully restored, and how impacts from local restoration are affected by wider landscape factors. Understand trade-offs/ benefits of restoration for multiple impacts, and whether local-scale restoration has landscape-scale benefits (e.g., for connectivity, spillover effects, livelihoods). Develop prioritisation methods for identifying restoration locations that optimise multiple impacts.
4. **How to restore degraded forest?**	Active restoration (liana cutting, enrichment planting) accumulates carbon more quickly than passive in logged forests, but is more expensive. Active carbon restoration programmes support local livelihoods.	Passive restoration methods are more cost-effective, but benefits of active versus passive methods for carbon and biodiversity may differ, and will depend on local context.	Unlike carbon, there are few data comparing active versus passive restoration methods for biodiversity impacts, and whether active restoration benefits or harms nature. Unclear when active versus passive methods will deliver	Develop guidance on best methods for restoring for carbon and biodiversity impacts (e.g. active versus passive restoration methods). Better guidance on setting baselines and monitoring outcomes.

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Table 2 (*continued*)

Key questions	The current scientific evidence base to support action	Recommendations based on current evidence	Current unknowns, knowledge gaps and challenges	Moving forwards: information generation
	Active restoration (e.g., enrichment planting) is needed at sites where natural regeneration is disrupted. Species richness recovers quickly in large tracts of naturally (passively) regenerating forest.		best carbon impacts (e.g., no thresholds or baselines have been set for when active methods are needed, relative to cost). It will be challenging to agree appropriate metrics for assessing biodiversity impacts, which will depend on species/taxa/functions being monitored, and local context (e.g., due to differences in baselines and regrowth).	Develop guidance on the usefulness of biodiversity impact metrics that focus on indicator species (e.g., rare, threatened or endangered species), versus groups with important ecosystem functions (e.g., dung beetles; seed dispersers), and iconic umbrella species (e.g., tigers, orangutans).
5. **Who benefits from restoration impacts?**	Forest restoration that successfully delivers carbon and biodiversity offsetting will help companies meet their nature recovery and net-zero carbon pledges. Co-designed forest restoration projects can benefit local livelihoods, providing incomes and ecosystem service benefits (e.g., improved water quality). Forest restoration in the wider landscape may 'spillover' to provide local biodiversity and ecosystem benefits in adjacent habitats (e.g., decomposition, pollination, pest control services and enhanced species richness).	Forest restoration projects need to be co-designed to ensure they are fit-for-purpose to deliver carbon and biodiversity benefits for funders and local communities.	Better understanding of impacts for local communities and benefits/dis-benefits of restoration. Better monitoring and assessments of restoration impacts. Better processes are needed to agree allocation of carbon benefits from restoration to company versus national/state government commitments. Better understanding of the socio-economic barriers and enablers for restoration. Financial market prices for carbon credits in 2021 were too low to offset the costs of active restoration.	Development of robust verification of restoration success to increase consumer confidence in the capability of industry to meet its net-zero and nature targets. Better guidance on effective co-design practices of restoration projects with local communities from the outset, to ensure long-term success. Development of mechanisms linking new restoration projects with funders and local stakeholders. Development of a social-science 'playbook' for addressing the socio-economic and political enablers and barriers for successful forest restoration. Development of biodiversity financing to support CBD (Convention on Biological Diversity)/COP 15 Post-2020 Global Biodiversity Framework.

Cook-Patton et al., 2020; Griscom et al., 2017). These nature-based solutions are especially relevant in rainforest habitats where primary productivity, carbon sequestration rates and levels of biodiversity in regenerating forests are high (Edwards et al., 2011a; Lewis et al., 2019; Zeng et al., 2020).

Forest restoration initiatives and tree planting schemes offer significant potential for carbon sequestration and storage (Bastin et al., 2019), and hence an incentive for the expansion of carbon credit schemes, which have stimulated interest among corporate and governmental sectors to invest in restoration programmes (reviewed by Seddon et al., 2021). For example, 2011 saw the launch of the Bonn Challenge (www.bonnchallenge.org), which promotes the restoration of 350 million ha of forest globally by 2030. Reforestation and forest restoration are also embedded in the Sustainable Development Goals (SDGs) (Lewis et al., 2019; www.sdgs.un.org/goals), Aichi Targets (Tobón et al., 2017; www.cbd.int/sp/targets), and Post-2020 Global Biodiversity Framework (www.cbd.int/conferences/post2020), whilst 2021 marked the start of the United Nations Decade of Ecosystem Restoration (2021–30; www.decadeonrestoration.org) and global summits to agree actions on climate change and nature recovery (United Nations Framework Convention on Climate Change: COP26 and COP27; Convention on Biological Diversity: COP15). Hence, there are opportunities for corporate finance to support restoration initiatives, but companies cannot make evidence-based choices if the scientific information required to guide investments has not been synthesised in a way that they can use, or there are knowledge gaps that limit evidence-based decision-making.

In this perspectives piece, we focus on Southeast Asia to illustrate the challenges that are faced by companies when choosing to support restoration initiatives. This perspectives piece has arisen from a collaboration between rainforest researchers, a multinational consumer goods company (Unilever), and a Southeast Asian rainforest NGO (SEARRP; South East Asia Rainforest Research Partnership) to address the challenges faced by industry in making decisions about funding restoration. We have jointly identified the aspects that companies need to address in their restoration actions in Southeast Asia, the scientific information already available to support such actions, as well as key knowledge gaps and research priorities. We identify the next steps for ensuring that decisions made by companies result in successful restoration projects that return positive impacts (Table 2). We frame our perspectives paper around the following five questions that companies need to address when making choices on projects to fund: (1) what impacts are to be delivered by the restoration project (i.e., carbon, biodiversity, livelihoods), how to identify the best (2) habitat types, (3) sites, and (4) methods for generating the most positive restoration impacts, and (5) which organisations share the benefits of the restoration impacts (e.g., carbon offsets). Our article is not only timely because global and national goals to tackle climate change and conserve biodiversity require private sector action of this type, but highly relevant to many companies funding and partnering in landscape restoration globally (Table 1). Given the urgency of addressing climate change and biodiversity loss (recognised as "core" planetary boundaries based on their fundamental importance for the earth system (Steffen et al., 2015)), companies need to be sure that their investments are directed appropriately to deliver immediate and meaningful positive change.

Our perspective focuses on Southeast Asian rainforests because they support unique animal and plant diversity (e.g., Myers et al., 2000; Slik et al., 2018; Sodhi et al., 2010), and are dominated by a single family of trees, the Dipterocarpaceae, of which more than 90% of the 510 species are restricted to Asia (Bawa, 1998). These forests have, however, been subject to significant pressures from logging (mainly of dipterocarps), expansion of oil palm and industrial plantations, as well as other human activities (e.g., Descals et al., 2021; Reynolds et al., 2011). Land use history varies across different regions of the world but is typically associated with a complex set of socio-economic and market development factors (Giacomin, 2018), as is evident in Southeast Asia. The Southeast Asia region offers significant opportunities for restoring cleared, fragmented and degraded forest landscapes and is attractive for the associated sustainability benefits of carbon sequestration, increased biodiversity and improved livelihoods. Successful restoration depends on the local context (Di Sacco et al., 2021), but the general principles, current scientific evidence, knowledge gaps and challenges, and research needs that we discuss in the context of Southeast Asia (Table 2) will apply more widely to companies wishing to support restoration projects in other tropical forest regions.

2. What are the desired outcomes of restoration?

For companies to make successful investment choices, reasons for initiating a forest restoration project need to be clearly defined and elucidated. Our review of 96 studies in Southeast Asia (Appendix A: Fig. S1a) revealed restoration in the context of biodiversity recovery, carbon accumulation, changes to forest structure, and tree regeneration potential based on the survival of planted seedlings (Appendix A: Fig. S1b-c). Companies can have high confidence in achieving successful impacts from carbon restoration because there are relatively robust protocols available to measure pre-restoration baselines and impacts (e.g., Malhi et al., 2021). By contrast, projects focused on restoring biodiversity are more risky for companies because the appropriate metrics to measure impacts are less well established and are likely to be more complex than measuring carbon stocks and accumulation (see Section 5 below). The number of trees per unit area (e.g., ha) is a commonly used measure of tree or plant density to compare across restoration sites (e.g., Viani et al., 2018). However, measuring density of animal species is more difficult, as it is often challenging to ascertain the relative abundance of any given species (e.g., from point count surveys of birds) or the density of animals within a given area (e.g., from mist-net surveys of birds or camera trapping of mammals). Biodiversity metrics will also be especially challenging to develop for mobile species, which move widely across landscapes due to their large home ranges (e.g., hornbills, orangutans; Ancrenaz et al., 2021; Corlett, 2009), and so any outcomes of restoration will need to be disentangled from wider landscape effects. Field surveys of most taxa, other than iconic vertebrates and a few invertebrate groups such as butterflies, ants and dung beetles, are also hampered by difficulties with identification and lack of standardised sampling methods. Guidelines are needed to establish appropriate metrics of restoration success for faunal diversity, e.g., for site-level species richness, community composition and functional diversity. If the outcome of restoration is for a specific endangered species, then guidelines for quantifying abundance trends are needed. Ideally, a number of indicator groups (e.g., birds, fruit-feeding butterflies; see Barlow et al., 2007) would be included, to span a range of ecosystem functions.

2.1. Case study 1: An example of corporate ambitions for restoration – the Unilever Compass

The Unilever Compass strategy articulates several commitments towards improving the health of the planet, focusing on climate action, protecting and regenerating nature and contributing to a waste-free world (https://assets.unilever.com/files/92ui5egz/production/ebc4f41b-d9e39901ea4ae5bec7519d1b606adf8b.pdf/Compass-Strategy.pdf). For example, Unilever is committed to achieving a deforestation-free supply chain by 2023, and to help protect and regenerate 1.5 million ha of land, forest and oceans by 2030. Commitments are focused on palm oil, paper and board, cocoa, tea and soy. Current examples include: (1) tree planting in Côte d'Ivoire linked to a key cocoa growing region for the Magnum ice cream brand (https://www.magnumicecream.com/uk/planet/tree-planting-programme.html);(2) restoration of ecological corridors via *the World Wide Fund for Nature (WWF) Sabah Landscapes programme, supporting the Roundtable on Sustainable Palm Oil (RSPO) certification of 60,000 ha of oil palm plantation (https://www.unilever.com/news/news-and-features/Feature-article/2021/how-we-are-working-with-wwf-to-restore-forest-ecosystems.html); and (3) IDH (the sustainable trade initiative) coalition working in Aceh Tamiang to achieve a production, protection and inclusion (PPI) model surrounding the fragile forests of the Leuser Ecosystem, focusing on forest protection and reforestation (https://www.idhsustainabletrade.com/news/unilever-and-idh-commit-1–5 m-euro-for-sustainable-sourcing-in-indonesia/). A €1 billion Climate & Nature fund will be used over the next ten years to further invest in landscape restoration and reforestation projects, and identification of best practices is critical for the success of such projects.*

3. Which types of habitat will deliver the best restoration impacts?

Company decisions around forest restoration initiatives may be well-intentioned, but reforestation best-practices are complex, and there can be unintended negative consequences associated with such activities (Seddon et al., 2021). For instance, reforesting areas that have been cleared for agriculture can lead to food insecurity and the displacement of existing croplands, leading to deforestation elsewhere ('leakage' effects) (Meyfroidt et al., 2010). Planting monocultures or tree plantations of fast-growing, non-native species, which is considered a restoration measure by some initiatives (see Bechara et al., 2016; Lewis et al., 2019), will not enhance local biodiversity and may not capture as much carbon in the long term as restoring native forest (Lewis et al., 2019; Di Sacco et al., 2021). There are also many socio-economic factors to consider when selecting areas for reforestation (Di Sacco et al., 2021; Zeng et al., 2020), including issues of governance and land tenure which need to be considered to avoid social conflict or inequity arising from restoration schemes that are implemented without appropriate stakeholder engagement (e.g., Holl and Brancalion, 2020).

Restoring degraded areas of forest has been proposed as a cost-effective way to increase carbon stocks without increasing forest extent (Brancalion and Chazdon, 2017). For example, enrichment planting of degraded dipterocarp forest is between ~10%−30% of the cost of restoring cleared land (Kettle, 2010). However, the extent and location of degraded forest available for restoration is

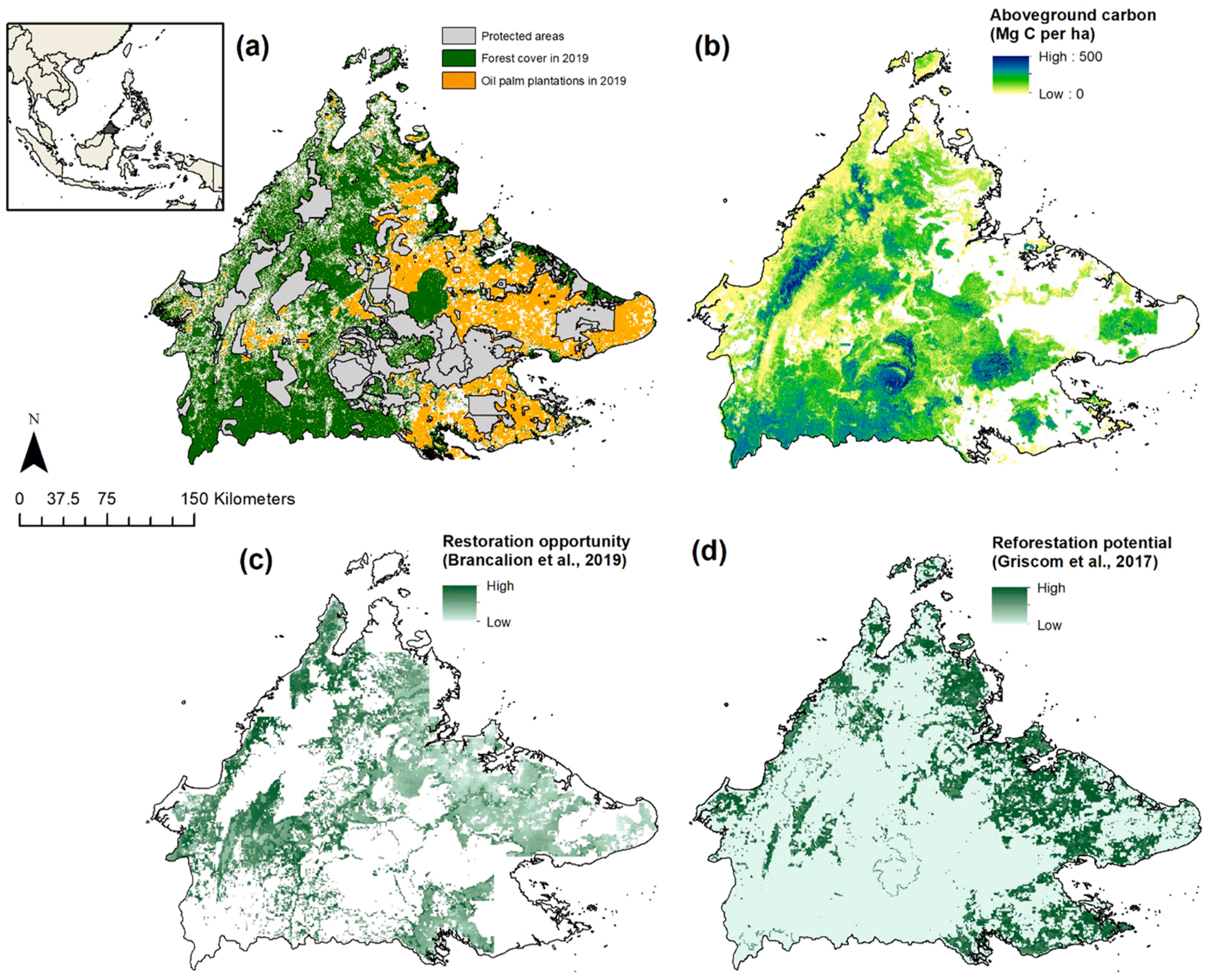

Fig. 1. Map of Sabah (Malaysian Borneo) illustrating the types of information that can be used for identifying restoration opportunities. This includes fine-scale information such as (a) current forest cover, agricultural areas (i.e., palm oil), and the Protected Area network, and (b) assessment of aboveground carbon (in units of megagrams (Mg = metric tons) of carbon (C) per hectare (ha); not including areas of oil palm and mangroves; Asner et al., 2018). Previous studies have used this type of information to map (c) restoration opportunities (Brancalion et al., 2019) and (d) reforestation opportunities (Griscom et al., 2017); we have removed the units from maps (c) and (d) as we do not wish to compare specific values, but instead highlight differences in proposed opportunities for restoration and reforestation. Data plotted in (a) are Protected Areas (designated and inscribed, downloaded from www.protectedplanet.net/ on 15th April 2021), forest cover in 2019 (downloaded from https://earthenginepartners.appspot.com/science-2013-global forest/download_v1.7.html; version 1.7, on 9th June 2020 and assuming a 60% tree cover threshold; see Hansen et al., 2013) and closed canopy oil palm plantations (both industrial and smallholders) in 2019 (downloaded from https://zenodo.org/record/4473715, version v0, on 2nd December 2020; see Descals et al., 2021).

unclear. Identifying areas of natural forest regrowth with the greatest carbon accumulation potential has been attempted at a global scale (Cook-Patton et al., 2020) and global maps showing restoration (e.g., Brancalion et al., 2019) and reforestation opportunities (e.g., Cook-Patton et al., 2020; Griscom et al., 2017) provide an indication of potential locations to focus efforts. However, there is little overlap in the locations identified in these different studies, due to differences in assumptions of the types of habitat that could be restored, sometimes including agricultural areas (Fig. 1). Many areas of Southeast Asia, such as the island of Borneo, were probably almost completely covered by forest historically and so all areas are 'ecologically appropriate' for forest (Griscom et al., 2017), even if they have been cleared and converted to other land-uses (e.g., oil palm plantations; Fig. 1). Restoring high yielding oil palm to natural forest is likely to be highly detrimental for both smallholder livelihoods and the local economy. Thus, it is unlikely that these areas would be considered as restoration opportunities, except in very low yielding areas.

There are opportunities to restore degraded forests throughout Southeast Asia because many areas have been repeatedly logged and heavily degraded since industrial-scale dipterocarp timber extraction began in the 1970 s (Reynolds et al., 2011). In Sabah (North Borneo) for example, conventional commercial logging took place in many areas from the 1970 s onwards and timber extraction rates consistently exceeded 10 million m^3 per annum (Reynolds et al., 2011). These conventional logging techniques are based on a minimum harvesting diameter of 60 cm dbh and bulldozers are used to make skid trails and to extract logs (see Pinard et al., 2000), causing extensive damage to forest structure. Non-harvest trees are crushed by tractors and falling timber and roads and skid trails compact soils and reduce the amount of ground vegetation (Wilcove et al., 2013). These unsustainable logging practices have resulted in highly degraded forests with limited current timber value, providing opportunities for restoration. For example, on Borneo, about half (46%) of the remaining forest area in 2010 had been logged (Gaveau et al., 2014), providing opportunities for biodiversity (Edwards et al., 2009) and carbon restoration (Philipson et al., 2020). High resolution maps of degraded forests (e.g., current carbon stocks; Fig. 1b) are needed, along with input from local stakeholders to identify suitable sites and native species to restore. High resolution satellite data such as Sentinel-2 (10 m resolution; https://sentinels.copernicus.eu/web/sentinel/home; also see Phiri et al., 2020 for review) and Global Ecosystem Dynamics Investigation (GEDI) products (25 m resolution; canopy top height, canopy cover fraction etc.; https://gedi.umd.edu/data/products/) have the potential to guide the identification of areas of degraded forests to restore, whilst drone images can be used at a smaller scale (Harrison and Swinfield, 2015). However, there is still considerable uncertainty and variability in how carbon accumulates over time from natural forest regrowth (Cook-Patton et al., 2020), particularly with respect to reference baselines (i.e., degraded forest versus cleared forest baselines) and local context, such as size and isolation of restored sites (i.e., proximity to natural source populations for seeds and animal biodiversity). Companies currently need a better understanding of such uncertainty to determine the likelihood of achieving any specific restoration targets.

Companies also need information on whether restoration projects will deliver sufficiently large benefits (carbon and/or biodiversity) to meet their climate and nature commitments. Knowledge and information sharing with local initivies such as the Asia Pacific Biodiversity Observation Network (APBON; https://geobon.org/bons/national-regional-bon/regional-bon/asia-pacific-bon/) could provide opportunites to identify and monitor suitable restoration sites. APBON is a network of institutions and research groups in the Asia-Pacific region that contribute to and use a knowledge resource base for conserving biodiversity and ecosytems (Takeuchi et al., 2021), and members currently have a number of in-situ monitioring sites across the Asia-Pacific region. These sites were established to survey plant species diversity and forest dynamics (Takeuchi et al., 2021), but such long-term monitoring data, as well as the local scientific knowledge base, will aid decision making.

4. Which sites will deliver the greatest beneficial impacts?

Across Southeast Asia, many areas of degraded forest are available for restoration, such as heavily logged forests, which are no longer financially viable for timber and so are vulnerable to conversion, so called 'restoration concessions' (Harrison et al., 2020). There are also opportunities to restore heavily degraded forest set-asides within agricultural areas (e.g., riparian buffer areas, and forest areas supporting High Conservation Value (HCV) and High Carbon Stock (HCS) within RSPO member plantations (Brown et al., 2013; Rosoman et al., 2017)).

Companies with commercial interests in particular regions, such as consumer goods companies who source palm oil from Southeast Asia for their products, could focus on opportunities within their supply chains and restore remnants of HCV/HCS forest within plantation landscapes. These forest remnants range from small, isolated forest fragments to larger areas of forest that are connected to existing Protected Areas (see Fleiss et al., 2020), and could provide opportunities for restoration to benefit sustainable practices in company supply chains/sheds. Restoring larger forest patches will provide greater opportunities for carbon sequestration due to detrimental edge effects causing high tree mortality in small fragments (Chaplin-Kramer et al., 2015; Laurance et al., 2011), because very small forest remnants will be completely edge-affected (i.e., subject to physical and biotic changes associated with the abrupt edges of forest fragments bordering agriculture and other non-forest areas; Laurance et al., 2018). Larger forest patches also support more species (Lucey et al., 2017) and so restoration to improve the quality of large forest patches is also likely to produce positive biodiversity outcomes. Nonetheless, small forest remnants could be targeted for restoration if they provide stepping-stones for mobile animals (Ancrenaz et al., 2021; Barbosa et al., 2017), connecting larger areas of forest and permanent forest reserves and supporting meta-populations of species (e.g., orangutan *Pongo spp.*; Ancrenaz et al., 2021). The detrimental effects of fragmentation on biodiversity are well documented (see synthesis by Haddad et al., 2015). However, there are currently no guidelines on the minimum size of forest areas to restore for long-term success for biodiversity restoration, and restoration benefits may not scale linearly with site area.

Restoration could focus on riparian buffer strips, which can support high carbon forest and relatively high diversity in agricultural areas (Deere et al., 2022; Mitchell et al., 2018; Pashkevich et al., 2022). Given their linear characteristics, these buffer strips can also provide corridors between larger areas of forest, enhancing connectivity (Gray et al., 2019). Thus, restoring riparian areas where they do not currently occur, or where regulations require them to be wider, and improving forest quality of existing riparian strips, will likely provide multiple conservation outcomes. These outcomes include important ecosystem services such as improving water quality and preventing soil run-off and erosion (Tabacchi et al., 2000), and conserving iconic endemic species such as Proboscis monkeys (*Nasalis larvatus*) (Sha et al., 2008). Tree planting will be needed where riparian forest areas have been cleared, or are too narrow (e.g., RSPO guidance on buffer width varies depending on river width and situation; Lucey et al., 2018). However, restoring riparian buffers and conservation set-asides may not meet the needs of large-scale restoration projects, if investment returns are low, and it is likely that many corporate initiatives will focus on restoring large areas to reduce costs and with the potential to provide greater benefits for carbon and biodiversity (e.g., if restoration improves connections between larger forest reserves and Protected Areas).

There are considerable opportunities for companies to be involved in restoring large areas of currently unprotected and degraded forest in the wider landscape (Harrison et al., 2020). These restoration sites provide substantial opportunities for carbon sequestration and biodiversity conservation (see Case Study 2: Restoration of the Central Forest Spine, Peninsular Malaysia). There are also opportunities for restoration to re-establish important forest connections, to link up networks of Protected Areas, and improve connectivity along elevation gradients to support climate-driven range shifting by species to cooler refuges (Scriven et al., 2015). Restoration of forest corridors will help conserve populations of iconic species, such as orangutans (*Pongo spp.*) and elephants (*Elephas maximus borneensis*) (e.g., Williams et al., 2020). The designated protected status of such sites would need to be upgraded to demonstrate their projection 'in perpetuity' for funders. There are many options for choosing the most effective sites to restore in order to deliver the greatest benefits for nature recovery and we highlight a number of possibilities. However, any benefits will be context and landscape dependent, and different companies will require different restoration outcomes. Focusing restoration efforts on large tracts of degraded forest will likely provide the largest benefits for carbon and biodiversity, but this may not always be possible in human-modified landscapes, where only small remnants of forest persist.

4.1. Case study 2: A landscape-scale restoration project - restoration of the Central Forest Spine, Peninsular Malaysia

*In 2010, the Forestry Department of Peninsular Malaysia developed the Central Forest Spine (CFS) Master Plan for Ecological Linkages in Peninsular Malaysia (*FDTCP Federal Department of Town and Country Planning, 2009; Maniam and Singaravelloo, 2015*) with the aim of guiding restoration that would improve connectivity between the remaining CFS forest blocks and Protected Areas (Appendix A:* Fig. S2*; e.g., restoring corridors and stepping-stone habitat), with a particular focus on conserving iconic species such as tigers (*Panthera tigris*), tapirs (*Tapirus indicus*), and elephants (*Elephas maximus*) (*Brodie et al., 2016*). The CFS provides considerable opportunities for forest protection (less than 20% of the CFS is currently protected) and restoration, because much of the area has been degraded by multiple rounds of selective logging and fragmented by agricultural and urban development. Restoration within the CFS is likely to be prioritised in the revised CFS Master Plan, which is currently being drafted, and will include recommendations to restore and re-establish forest cover in all key ecological CFS linkages identified in the original plan and which cover over 350,000 ha. Restoration in these areas, and through the wider CFS, has the potential to yield multiple conservation benefits for biodiversity, carbon and enhanced connectivity and is consistent with Malaysian Government commitments to plant 100 million trees between 2020 and 2025 as part of its 'Greening Malaysia' agenda. Local stakeholder support, including government-community-corporate partnerships, will be crucial if these benefits, and improved livelihoods of forest-dependent communities, are to be realised. We highlight the CFS as an area where forest restoration is likely to provide considerable benefits for carbon sequestration, biodiversity conservation and forest connectivity between Protected Areas. Investing in initiatives/landscapes such as this, will ensure that restoration projects funded by companies deliver multiple conservation benefits.*

5. How to restore degraded forest?

Forest areas can be restored through active or passive methods, which differ in their restoration costs and benefits. Methods of active restoration include enrichment planting with nursery-grown seedlings or seeds collected from mother trees (Harrison and Swinfield, 2015), silviculture techniques (liana cutting, thinning of saplings) and topsoil replacement to boost forest recovery (Lamb et al., 2005; Shono et al., 2007; Zahawi et al., 2014). Passive restoration is achieved by protection from further disturbances to allow natural regeneration to occur and may involve fencing off areas for protection from livestock grazing (Shono et al., 2007; Zahawi et al., 2014). Currently, much information about regeneration of Southeast Asian rainforests comes from studies comparing forest recovery after disturbance relative to baselines in nearby undisturbed forest or unrestored forest (i.e., 'space-for-time' studies of natural regeneration) (see Appendix A: Table S1). However, a few Southeast Asia studies have directly compared active versus passive methods. For example, Philipson et al. (2020) found that active restoration (a combination of climber cutting to prevent lianas competing with trees in disturbed secondary forests and enrichment planting) enhanced aboveground carbon recovery rates from commercial logging by more than 50% compared with passive restoration (from 2.9 for passive to 4.6 Mg C ha^{-1} yr^{-1} for active restoration), implying recovery in ~40 years, compared with ~60 years under passive restoration. However, other studies report significantly higher benefits from passive restoration for some aspects of vegetation structure (Crouzeilles et al., 2017; e.g., for density and height), or no differences in recovery in actively versus passively restored sites on former agricultural land (Meli et al., 2017). This highlights a lack of consensus in this respect, and there is limited guidance on when active versus passive methods will deliver the highest carbon impacts. Thus, no thresholds or baselines have been set for when active methods are needed, relative to operational costs. Moreover, the high costs of active regeneration methods mean that carbon prices will need to rise substantially in order to break-even with costs of enrichment planting, which Philipson et al. (2020) estimate at ~\$1500 to \$2500 ha^{-1} (also see Warren--Thomas et al., 2018).

Active methods may be more effective for carbon outcomes in Southeast Asian dipterocarp-dominated forests due to dipterocarp supra-annual patterns of mass fruiting, which may be disrupted in highly degraded sites (Curran et al., 1999). The seeds of dipterocarp trees are also wind dispersed (Smith et al., 2015), leading to reduced seedling recruitment if 'mother' trees are absent (Stride et al., 2018), but less sensitive to the loss of vertebrates (e.g., from poaching) than if their seeds were dispersed by animals. Therefore, active restoration (i.e., enrichment planting of dipterocarp seedlings; see Case Study 3 – Enrichment planting to improve the conservation value of forest remnants) may be needed in highly degraded areas and isolated forest fragments in Southeast Asia in order to improve tree regeneration rates (Yeong et al., 2016). However, there are exceptional concentrations of dipterocarp species in Southeast Asia, and hence many different types of dipterocarp-dominated forests (Raes et al., 2014; Slik et al., 2018), which should be taken into account when enrichment planting is carried out. Enrichment planting may not be necessary in larger forest areas, which are likely to regenerate naturally depending on their size, logging history and intensity, and proximity to other areas of forest in the wider landscape. Reforestation in non-forest areas, such as restoration of riparian buffer strips, could be achieved by planting fast-growing, light-demanding tree species (Brancalion et al., 2020), or using 'applied nucleation' in which small 'islands' are reforested within cleared areas, that then encourage natural regeneration more widely (Bechara et al., 2016; Holl et al., 2020).

By comparison with carbon, studies examining biodiversity outcomes for passive versus active restoration methods in Southeast Asian dipterocarp forests are limited, but a global meta-analysis concludes that natural regeneration delivers better restoration success for biodiversity than does active restoration (Crouzeilles et al., 2017; although the difference was only significant for one taxonomic group: plants). This finding is supported by studies in Southeast Asia, where bird and dung beetle communities were found to be similar in sites with active restoration and naturally regenerating forest (Ansell et al., 2011; Cerullo et al., 2019), suggesting that active management interventions to increase carbon stocks do not also increase biodiversity recovery. Moreover, other studies report that active restoration can actually be detrimental for animal biodiversity (Cosset and Edwards, 2017). Hence, responses of biodiversity to restoration are idiosyncratic (Edwards et al., 2011b) and likely to be dependent not only on restoration methods, but on the local land-use history and previous forest disturbances (Crouzeilles et al., 2016; Meli et al., 2017), making biodiversity outcomes difficult to predict. There is not yet a clear agreement on how best to restore for biodiversity, but areas of high carbon are also likely to support high faunal biodiversity (Deere et al., 2018; Williams et al., 2020), particularly rare and threatened forest-dependent animals. Currently, more guidance is needed on whether active or passive restoration will be more beneficial for delivering both carbon and biodiversity co-benefits, and we highlight this as a key knowledge gap to be addressed so that clearer recommendations for companies investing in restoration projects can be provided (see Table 2).

5.1. Case study 3: An example of active forest restoration - enrichment planting to improve the conservation value of forest remnants

*Heavily degraded remnants of natural forest remain within oil palm landscapes, providing opportunities to restore carbon and biodiversity (*Fleiss et al., 2020*). However, there are currently no guidelines for restoring these remnants and so we have examined the viability of enrichment planting as a potential management tool to enhance the conservation value of forest remnants. We planted dipterocarp seedlings in eight forest remnant sites (ranging from 3 to 3529 ha in size in Sabah, Malaysian Borneo;* Yeong et al., 2016*). Surveys 18 months after planting showed that survival rates of planted seedlings were equally high in remnants and continuous forest control sites (~60% survival;* Yeong et al., 2016*). This success of enrichment planting was still evident 6 years after planting, where our re-surveys showed that dipterocarp seedling survival was ~10% higher in remnants (mean = 37% survival; see Appendix A:* Fig. S3a*) than in continuous forest sites (mean = 25%), and seedling growth rates in remnants were nearly twice those of control sites (see Appendix A:* Fig. S3b*), due to the higher light environments in the degraded remnants. Thus, enrichment planting could be a useful management strategy to restore carbon in remnants, with likely co-benefits for plant biodiversity (*Fleiss et al., 2020*). Further research is needed to determine whether complementary management activities such as liana cutting (see* Marshall et al., 2020*) would also be beneficial, and the impacts for biodiversity.*

6. Who benefits from restoration impacts?

The long-term success of restoration projects depends on co-design with local stakeholders from the outset, to ensure free, prior and informed consent and ensure respect of their cultural and ecological rights (see review by Seddon et al., 2021). Local communities may directly benefit from restoration if they receive income from their involvement in active restoration programmes and forest monitoring, as well as benefitting from any enhancement to ecosystem services from restoration (e.g., from restoration of riparian buffer zones and improvement to water catchment hydrology and water quality). Forest restoration will also decrease the vulnerability of local communities to climate change (IPCC, 2022), for example, mangrove forest restoration buffers communities against storm surges and controls erosion (CBD Convention on Biological Diversity, 2009; IPBES, 2018).

Well-designed restoration projects can therefore benefit local communities, who are often negatively impacted by forest degradation where poverty is linked to the loss of biological resources. Local communities rely on forest ecosystem services such as fuel woods and Non-Timber Forest Products (NTFPs; e.g., bush meat, honey, wax, natural medicines), as well as clean water regulation and spiritual services (Harrison and Swinfield, 2015; IPBES, 2018). Restoring community forests for biodiversity may therefore provide co-benefits for local people, but this needs to be properly managed to ensure benefit-sharing and the fair distribution of opportunities for communities to earn new income (Pilumwong, 2017). For example, tropical peatland forests play a vital role in regulating hydrology and climate, and can support biodiversity and livelihoods (IPBES, 2018; Joosten et al., 2016), but restoration initiatives fail if socio-economic factors are not adequately considered (see Mishra et al., 2021 for a recent review), particularly if peatland forest is restored on what is currently cropland (IPCC, 2022; Mishra et al., 2021). As anthropogenic pressures on natural systems become more severe, there is increasing mutual influence and feedback between socioeconomic systems and natural ecosystems (Yu et al., 2021). Payments for Ecosystem Services (PES) are becoming an increasingly important policy tool for coordinating ecological protection and regional socioeconomic development (see review of spatial targeting methods by Guo et al., 2020), whilst toolkits such as TESSA (Toolkit for Ecosystem Service Site-Based Assessment; http://tessa.tools/) can also be used to assess the consequences of change in land-use for different stakeholder groups (Peh et al., 2013).

Successful restoration must take account of land tenure considerations and the need to agree the allocation of carbon benefits from restoration. For example, a previous restoration project in Sabah, initiated in 1992, allocated carbon income to the main project funder, while potential future timber revenues (should the project area ever be harvested) were allocated to the state government foundation (Yayasan Sabah; FACE the Future, 2011). In a more recent forest-based carbon financing project in Sabah, involving the same state government foundation, potential carbon revenues are split between the foundation, Sabah Forestry Department and a UK-based funding agency (Glen Reynolds, pers. com). Sharing carbon benefits in this way can help reduce financial risks and ensure a more equitable split of benefits of restoration. Increases in demand for access to restoration schemes makes it vital that poor-quality and/or poorly managed projects are avoided, but restoration decisions to achieve carbon sequestration benefits need to be taken soon if they are to contribute to reducing peak global warming this century. Mechanisms to link funders and investors with projects may be helpful, such as the World Resources Institute (WRI) TerraMatch global online platform that links private sector funders with vetted projects to restore degraded and deforested land (https://www.terramatch.org/), or the recently launched Climate Impact X platform in Singapore (https://www.climateimpactx.com/).

Building partnerships between private sector companies, government and non-governmental organisations will help finance reforestation and restoration projects. Projects that have co-benefits for enhancing biodiversity and mitigating climate change, while also supporting local livelihoods, will help meet developmental aspirations linked to the SDGs (Pörtner et al., 2021). However, achieving multiple goals and co-benefits may require accepting trade-offs (Holl and Brancalion, 2020), and restoration must be based on best practices to ensure that local communities benefit and are not negatively affected (Di Sacco et al., 2021).

7. Conclusions and summary of challenges and priorities for future research

We examined five key questions that companies need to consider when making decisions about how to meet their climate and nature commitments, and to ensure corporate investments in restoration projects deliver the greatest return in terms of beneficial impacts. In Table 2, we have summarised the key conclusions from our synthesis of current information, highlighted the knowledge gaps and outlined next steps for research to fill these gaps.

Our aim was to synthesise scientific information on restoring for carbon and nature to aid companies in financing restoration projects. We acknowledge that many climate and nature goals set by large companies are voluntary, but the trend is towards greater accountability and transparency of performance. This is being facilitated by the implementation of climate reduction targets in national legislation, a proposed target in the draft Global Biodiversity Framework (https://www.cbd.int/conferences/post2020/wg2020–03/documents) for governments to require companies to report on nature impacts, the financial sector's interest in sustainability ratings and performance, and activities such as the Science Based Targets Initiative (SBTi: https://sciencebasedtargets.org/), the Science Based Targets Network (SBTN:https://sciencebasedtargetsnetwork.org/), as well as the Carbon Disclosure Project (CDP: https://www.cdp.net/en). There is also an investor movement seeking mandatory business disclosure on nature; this is gaining traction via the Taskforce for Nature Related Financial Disclosures (TNDF: https://tnfd.global/), with a framework that seeks to identify nature related risks and opportunities.

Many companies are pledging net-zero carbon targets and to enhance and protect nature to satisfy consumer demands for sustainably sourced commodities. However, financing for biodiversity commitments are poorly developed compared with carbon financing, and significant improvements are needed to ensure better integration of biodiversity and climate change policy agendas (Pettorelli et al., 2021). Recent increases in the number of companies committing to net-zero will likely increase the number of restoration schemes. Companies need to make financing decisions by accessing the current scientific evidence-base, but new research is also needed to target knowledge gaps (Table 2). Both of these activities are urgently required to ensure that restoration projects successfully sequester carbon, boost biodiversity and benefit livelihoods. Of course, forest restoration initiatives should not detract from the need to conserve natural ecosystems and ensure that remaining areas of rainforest are protected.

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Author contribution statement

SS, HK, GR and JKH were involved in the project's conceptualization and funding acquisition, SS, HK, EW, SAS and JKH designed the study, EW, SAS and YKL conducted the research and analyses, SAS and EW wrote the first draft of the manuscript, with contributions and critical reviews from all authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02305.

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