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RESEARCH ARTICLE

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Using technology to improve the management of development impacts on biodiversity

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Abstract

The mitigation hierarchy (MH) is a prominent tool to help businesses achieve no net loss or net gain outcomes for biodiversity. Technological innovations offer benefits for business biodiversity management, yet the range and continued evolution of technologies creates a complex landscape that can be difficult to navigate. Using literature review, online surveys, and semi-structured interviews, we assess technologies that can improve application of the MH. We identify six categories (mobile survey, fixed survey, remote sensing, blockchain, data analysis, and enabling technologies) with high feasibility and/or relevance to (i) aid direct implementation of mitigation measures and (ii) enhance biodiversity surveys and monitoring, which feed into the design of interventions including avoidance and minimization measures. At the interface between development and biodiversity impacts, opportunities lie in businesses investing in technologies, capitalizing on synergies between technology groups, collaborating with conservation organizations to enhance institutional capacity, and developing practical solutions suited for widespread use.

KEYWORDS
biodiversity, environmental impact assessment and monitoring, no net loss and net gain, environmental management, mitigation hierarchy, technology

1 | INTRODUCTION

1.1 | Impacts of industrial-scale development on biodiversity

Despite increasing recognition of its importance, biodiversity is in precipitous decline (Díaz et al., 2019; Tittensor et al., 2014). Recent reports estimate that 75% of the terrestrial environment and 66% of the marine environment have been severely altered by human activity (Halpern et al., 2015; IPBES, 2019; Venter et al., 2016), and that between 1970 and 2014 populations of monitored species have declined by an average of 70% (WWF, 2018). This decline is largely driven by the continued growth of the global economy (Hooke et al., 2012; IPBES, 2019; Maxwell et al., 2016). From aquaculture and forestry to mining, consumer goods, and infrastructure, industrial development across sectors is closely tied to biodiversity loss. Business operations and supply chains act to increase the production and movement of goods, often at the expense of natural ecosystems through increasing habitat loss, fragmentation, pollution, invasive species introductions, and overexploitation (Díaz et al., 2019; Krausmann et al., 2017). Consequently, biodiversity loss is recognized as a major global challenge for the private sector presenting operational, financial, and reputational risks (Global Canopy & Vivid Economics, 2020; WEF, 2021).

Increasing business awareness of the challenge posed by biodiversity loss is reflected in companies' efforts to develop and implement targets for reduction of their biodiversity impact (de Silva et al., 2019), tools and frameworks to measure those impacts (Addison et al., 2018; Addison et al., 2020), and strategies to address them. The Convention on Biological Diversity's post-2020 framework is likely to set ambitious global targets for biodiversity that will require a concerted response across all sectors of society. Alignment of the private sector with these goals represents an opportunity for large-scale change to help bend the curve of biodiversity decline (Folke et al., 2019; Mace et al., 2018).

1.2 | The mitigation hierarchy as a key tool for addressing impact

The mitigation hierarchy (MH) is a well-established practical framework to help business mitigate biodiversity impact. The hierarchy prioritizes avoidance of impacts first and foremost, followed by minimization, restoration measures, and, if those steps fail to mitigate any residual impacts, offsetting (Business and Biodiversity Offsets Programme [BBOP], 2012; CSBI, 2015) (Figure 1). Implementation of the hierarchy is central to good-practice management of biodiversity impacts, and for achieving the no net loss (NNL) or net gain (NG) goals increasingly required by the private sector (de Silva et al., 2019; Equator Principles, 2020). The MH has recently been extended to a general framing (the "conservation hierarchy") intended to include all conservation activities (Arlidge et al., 2018) and it has been suggested as an approach that can help businesses and governments reach targets aligned with the CBD goals (Milner-Gulland et al., 2020).

Businesses are now increasingly impelled to implement the hierarchy. The hierarchy has become central to lenders' safeguard frameworks (including the Equator Principles) that determine if a project can be financed (Equator Principles, 2020; IFC, 2012). The hierarchy is also embedded in best-practice guidance and principles for achieving NNL or NG for biodiversity (e.g., BBOP, 2012; CSBI, 2015), targets which many businesses are now establishing voluntarily (de Silva et al., 2019). It is also increasingly recognized in national environmental regulations and implicitly encouraged in many, though not all, offset policies (zu Ermgassen, Utamiputri, et al., 2019). Some businesses are now explicitly using the approach to develop strategies to monitor and mitigate biodiversity impacts across their operations (Biodiversify & University of Cambridge Institute for Sustainability Leadership, 2020).

However, while a helpful conceptual framework, many companies do not yet engage with their biodiversity impact, and implementation of the MH in practice has faced criticism. For example, often avoidance measures are not applied early in project planning (Phalan et al., 2018), there is improper implementation or monitoring of outcomes (Tischew et al., 2010), while offsets face complex technical and practical challenges (Maron et al., 2016) and, at times, fail to achieve intended outcomes (zu Ermgassen, Baker, et al., 2019). This highlights the need to improve current practice to achieve better outcomes for biodiversity.

The reasons for inadequate implementation of the MH are varied and often context specific. Common constraints include, among

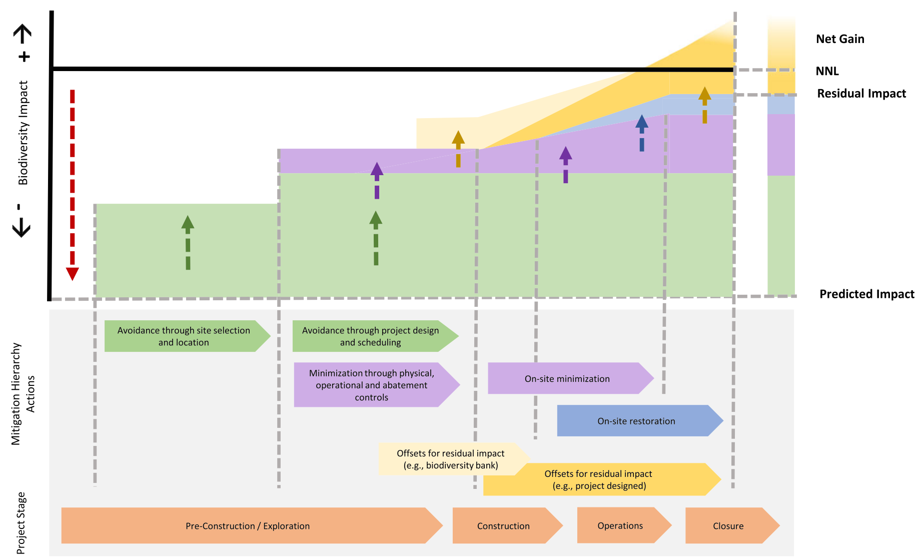

FIGURE 1 **The mitigation hierarchy**. In order to achieve NNL or net gain goals, a company will need to assess the potential impacts associated with a planned development (red), before designing mitigation measures throughout the project cycle (orange) to mitigate for that impact. Impacts should first be avoided (green) as a priority, then minimized to the greatest extent possible (purple). Restoration on site (blue) can further reduce impacts, before biodiversity offsets (yellow) are considered as a last resort to compensate for any residual impacts remaining. The timeline for mitigation relative to the project timeline is illustrative and indicative of common practice, but can vary depending on the context. For example, offsets may be secured earlier and without a time-lag through biodiversity banking programs that are available in some countries [Colour figure can be viewed at wileyonlinelibrary.com]

others, gaps in the availability, access, or awareness of relevant information on baselines and impacts (e.g., Jacob et al., 2016); high cost and/or low feasibility of collecting baseline and monitoring data (e.g., for bird and bat fatalities in offshore wind farms, Lindeboom et al., 2015, or cryptic species, Bain et al., 2014, Williams et al., 2018); absence of affordable and effective technical solutions for minimizing impacts (e.g., cost of burying power transmission lines to prevent bird collisions, Bernardino et al., 2018; ineffectiveness of fish ladders to maintain bi-directional migration, Agostinho et al., 2012); inadequate availability of finances and knowledge required for biodiversity impact mitigation (e.g., Krause et al., 2021); and limited empirical evidence for the effectiveness of mitigation options (Christie et al., 2020). The application of new technologies has potential to help overcome these challenges, increasing the feasibility and effectiveness of mitigation and monitoring (Bergal-Tal & Lahoz-Montfort, 2018; Joppa, 2015; Lahoz-Monfort et al., 2019; WILDLABS, 2016).

1.3 | Why and how new technologies are key to improving MH implementation

In recent decades, new technologies have enabled positive disruption, change, and innovation across many sectors. Biodiversity conservation is no exception, with rapid advances in technologies on many fronts, notably for collecting field data (Marvin et al., 2016; Pimm et al., 2015; Snaddon et al., 2013) and analyzing large datasets (Kelling, 2018; Marvin et al., 2016). For example, the increased availability, affordability, and discrimination power of satellite imagery have revolutionized data collection for ecological survey and monitoring (Pimm et al., 2015). Camera traps are another technology that has become more affordable, with models for a wide range of uses now commercially available, allowing data collection even for cryptic, difficult to survey species (Marvin et al., 2016).

These and other advances have helped to shift attitudes in the biodiversity community on the application of new technologies from initial mistrust and dismissal to general enthusiasm including calls for design and development of further technologies tailored to biodiversity conservation needs (Berger-Tal & Lahoz-Monfort, 2018). Nevertheless, it has been argued that biodiversity conservation is not taking full advantage of technology's potential, owing to inadequate development of widely applicable tools (because of, e.g., lack of commercial incentives, funding support, business models, or markets), lack of awareness and technical skills among users, and at times inappropriate use (e.g., without sufficient consideration of limitations or context) (Joppa, 2015; Lahoz-Monfort et al., 2019). The private sector has a long history of fostering technological development (e.g., aeronautics, computing, and communications), and in some cases, businesses are leading the way in developing and trialing technologies for conservation. For example, effective automated curtailment systems have been developed in the renewables industry to automatically detect at-risk birds and shut down wind turbines at risk of colliding with them (McClure et al., 2021), and online databases of biodiversity data are increasingly used by businesses to screen potential project sites and investments (e.g., IUCN, 2014). Yet in the most part, technology for biodiversity conservation has not been as fully embraced by the private sector as technologies in other realms of their operations.

To support effective implementation of the MH we need to take stock of different technologies' potential for biodiversity management, so as to identify the most promising targets for scaling-up their development and application (Iacona et al., 2019). However, the rapid pace of technological innovation creates a complex and confusing landscape that can be difficult to navigate. To address this issue, we here review recent advances in technological innovation, highlighting those existing and emerging technologies that may hold greatest potential for improving implementation of the MH, improving biodiversity outcomes, and enabling companies to achieve NNL/NG goals.

2 | METHODOLOGY

Between November 2018 and May 2019, we conducted a detailed three-part review of new and emerging technologies (Figure 2; Supporting Information). For the first stage, we conducted (i) a targeted review of academic and gray literature and (ii) a Google Scholar search to identify articles addressing technology use in conservation. For the targeted review, we identified ten reviews in the academic literature of technology use in conservation, and five annual horizon scans published between 2015 and 2019 in Trends in Ecology and Evolution (Supporting Information). The horizon scans used are published by an influential global collaboration of authors in both academia and conservation practice to identify emerging topics of importance for conservation (e.g., Sutherland et al., 2017). We screened all papers published in six leading journals focused on impact assessment and management between 2017 and 2018, going back to 2014 for three journals (Supporting Information). Where articles were identified as relevant based on their title and abstract, the documents were read in full, and information on each technology mentioned were extracted. Documents were deemed relevant if (i) they contained information on technology being used in biodiversity management or in the implementation of the MH or (ii) contained information on new technology (developed or in development) that has potential for mitigation hierarchy implementation. The targeted review was supplemented with non-governmental organization (NGO) reports and websites identified as highly relevant, the authors' knowledge of the MH literature, and referrals from colleagues at the authors' institutions (Supporting Information).

As well as the targeted literature search, a rapid search of the Google Scholar database was conducted to ensure important articles (and technologies) had not been missed during the targeted document review. The search string utilized in the search was as follows.

(“Biodiversity” AND “Technology”) OR (“Conservation” AND “Technology”) OR (“Environmental monitoring” AND “Technology”) OR (“Environmental management” AND “Technology”).

The search was conducted using the Google Scholar database in November 2018 and was limited to articles published after 2014. Screening of articles was limited to the first 750 results with the

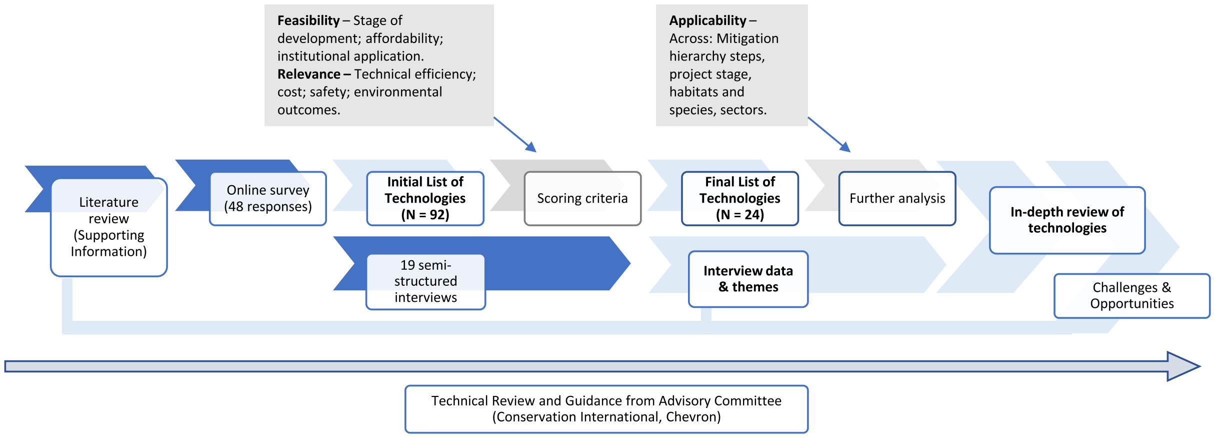

FIGURE 2 Technology review process [Colour figure can be viewed at wileyonlinelibrary.com]

results initially screened based on title (e.g., Godin et al., 2015). Those deemed relevant were then screened by either abstract, table of contents, or executive summary (whichever was available). If deemed relevant from this, the full text was then read, and relevant information was extracted for inclusion in the initial list of technologies. From the literature review, we identified 80 distinct technologies.

In April 2019, the literature search was supplemented by an online survey sent to individuals working in environmental management for business and technology application in conservation, and more widely via social media of our two organizations (The Biodiversity Consultancy & Conservation International). The survey asked participants to list up to three technologies (either existing or emerging) they believed had potential to improve the implementation of the MH (see Supporting Information for full question structure). Considering the wide dissemination of the survey to thousands of individuals (Supporting Information), the response rate was low with 48 responses received. Respondents were from a range of sectors (consultants, NGOs, governmental, intergovernmental, research, and private sector) and 29 different countries. The online survey identified 80 distinct technologies including 12 not identified in the literature review, forming an initial list of 92 distinct technologies.

We scored the technologies on this list for potential utility, compiled information on their use, and assessed the breadth of their applicability. To score the technologies, we defined seven criteria (see Supporting Information for details). Three criteria were based on feasibility of use ([i] Is the technology at a useable stage of technical development?, [ii] Is it currently affordable?, [iii] Can it be easily applied institutionally?) and four on the relevance to biodiversity management for business ([iv] Can it improve technical efficiency?, [v] Can it improve cost-efficiency?, [vi] Can it improve safety?, [vii] Can it improve environmental outcomes?). Scores between 0 (*low*) and 2 (*high*) were initially assigned for each criterion by T.B.W, then reviewed and agreed by all authors and by the project's advisory committee of experts (see Acknowledgements). Scores were summed to give an overall score for each technology (maximum total of 14).

Alongside scoring, we also collected information on the applicability of the different technologies for use: (i) at multiple stages of the MH, (ii) at multiple stages of the project cycle, (iii) for the management of different species and habitats, and (iv) by different industry sectors. However, these criteria did not influence final scores.

We selected the highest scoring 24 technologies for more detailed investigation, on the assumption that this sub-set, scoring 10 or more points in total, had the greatest potential for improving the application of the MH and thus biodiversity management. This shortlist of technologies was further validated via a suite of interviews with experts (see below). We focus our discussion on this final list of technologies which we categorized into six broad technology groups defined in consultation with the advisory committee for the project. More detail on the initial list is included in Supporting Information.

Finally, we also conducted 19 in-depth semi-structured interviews between April and June 2019. Interviewees had expertise in MH application and/or technology use in conservation and impact management. They were asked to identify technologies with most potential for use in the MH and provide case studies of their use, with questions framed around our scoring criteria (Supporting Information). Using purposive sampling, interviewees were selected to be representative of a broad range of stakeholder groups (Bernard, 2006) including: NGOs (six interviewees), industry organization representatives (one interviewee), academia (two interviewees), consultancy (two interviewees), and the private sector (eight interviewees) across a range of sectors including wind, finance, oil and gas, mining, and technology. Interviews were in English only. Females represented 32% of the final interviewees.

These interviews served to validate our selection of the final list of technologies as we found that in 93% of instances where interviewees referred to a technology, the technology was included in our final list. The interviews also allowed us to identify possible gaps in technology identification and supplement the in-depth analysis of high-scoring technologies. To this last part, we conducted a thematic analysis of the interviews, identifying themes, challenges, and opportunities for technological development in the future. Further detail on the methodology, the online survey structure, interview guide, informed consent process, and thematic analysis results are included in the Supporting Information.

2.1 | Technologies

We assigned the 24 technologies in our final list to six broad categories: mobile survey, fixed place survey, remote sensing, blockchain, data processing, and enabling technology (Figure 3).

2.1.1 | Mobile survey

This category encompasses technologies that collect data through a mobile platform include unmanned aerial vehicles (UAVs), unmanned submersibles, and GPS trackers. These technologies have rapidly developed over the last decade and are used widely across the project cycle to assess and monitor species and habitats. GPS technologies connect to global navigation satellite systems to track species presence and movements, while UAVs and unmanned submersibles can provide high-resolution habitat imagery less invasively and over large spatial scales, obtaining data that would be difficult, costly, or hazardous to collect with traditional techniques (Bicknell et al., 2016; Hodgson et al., 2018; Marvin et al., 2016; Vanreusel et al., 2016). For example, UAV's can collect data at 2-cm resolution (Wich & Koh, 2012) and can cover over 500 ha in a 1-h flight (Marvin et al., 2016). UAVs and submersibles with cameras can collect data on habitat extent, type, and quality (Wich & Koh, 2012), as well as species presence and abundance (van Andel et al., 2015). UAVs and submersibles can be retrofitted with specialized camera technologies (e.g., hyperspectral imagery, thermal infrared; Zhang et al., 2020), audio collection devices (e.g., hydrophones that enable audio surveys of marine species; Vanreusel et al., 2016), and devices for use in restoration (e.g., planting seedlings; BioCarbon Engineering, 2018) or invasive species control (Figure 4). The monitoring capabilities of these technologies are useful for monitoring the effectiveness of mitigation measures on species and habitats and for developing accurate, detailed biodiversity baselines which are vital for designing appropriate avoidance and minimization measures.

Commercially available GPS tags continue to improve in battery life and decrease in size (Hallworth & Marra, 2015), although are still too large for some taxa (e.g., insects) (Marvin et al., 2016). Costs for UAVs, GPS equipment, and unmanned submersible vary greatly depending on model and require training to use, although these skills are becoming more commonplace (e.g., UAV pilot training; Gommers, 2015). While models are commercially available for an increasing range of uses (e.g., Greene et al., 2014) and modular designs can increase flexibility and ease of field repair

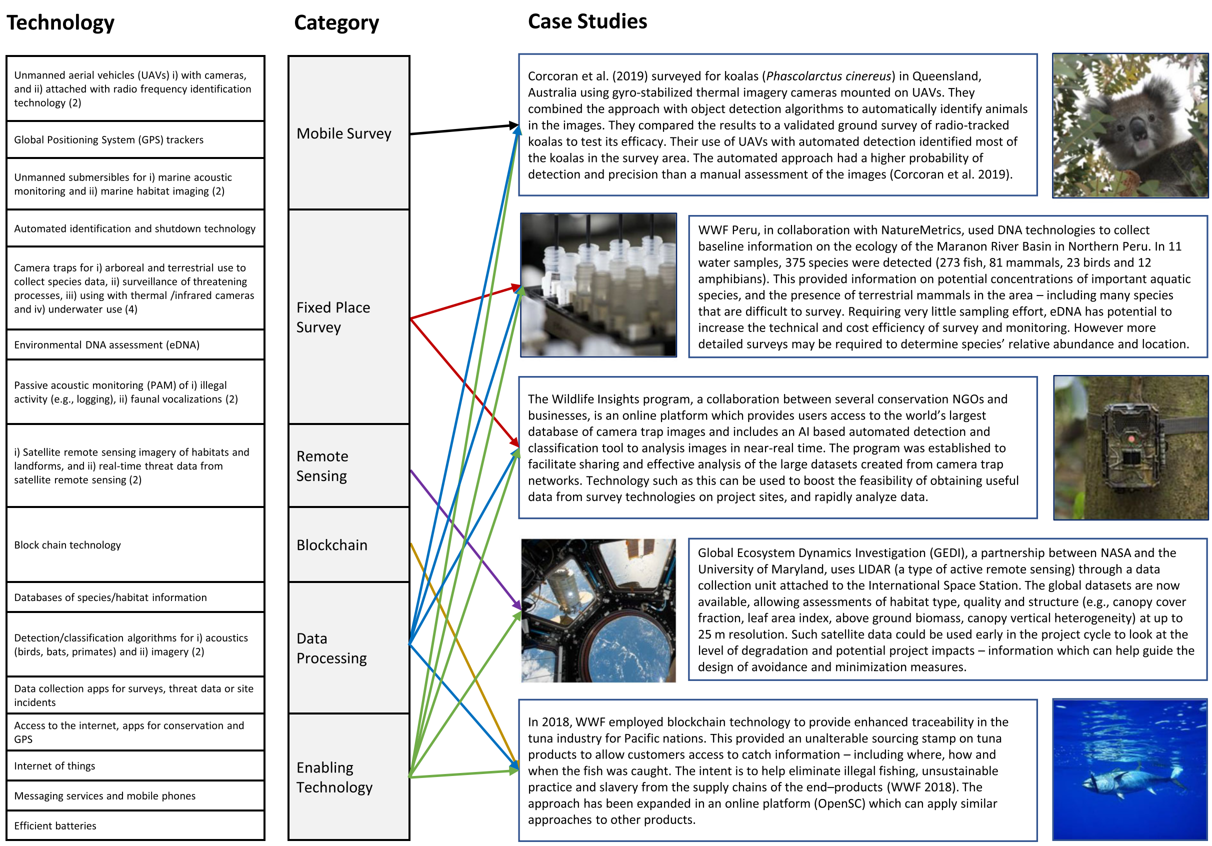

FIGURE 3 Shortlisted technologies and examples of technology use. The figure displays the 24 technologies included in our final list, the categories into which they were attributed, and five examples of technology use that could improve the application of the mitigation hierarchy. Where technologies have a number in brackets, this denotes the number of technologies in the final list within that grouping. Note the overlap of the case studies with data processing and enabling technology [Colour figure can be viewed at wileyonlinelibrary.com]

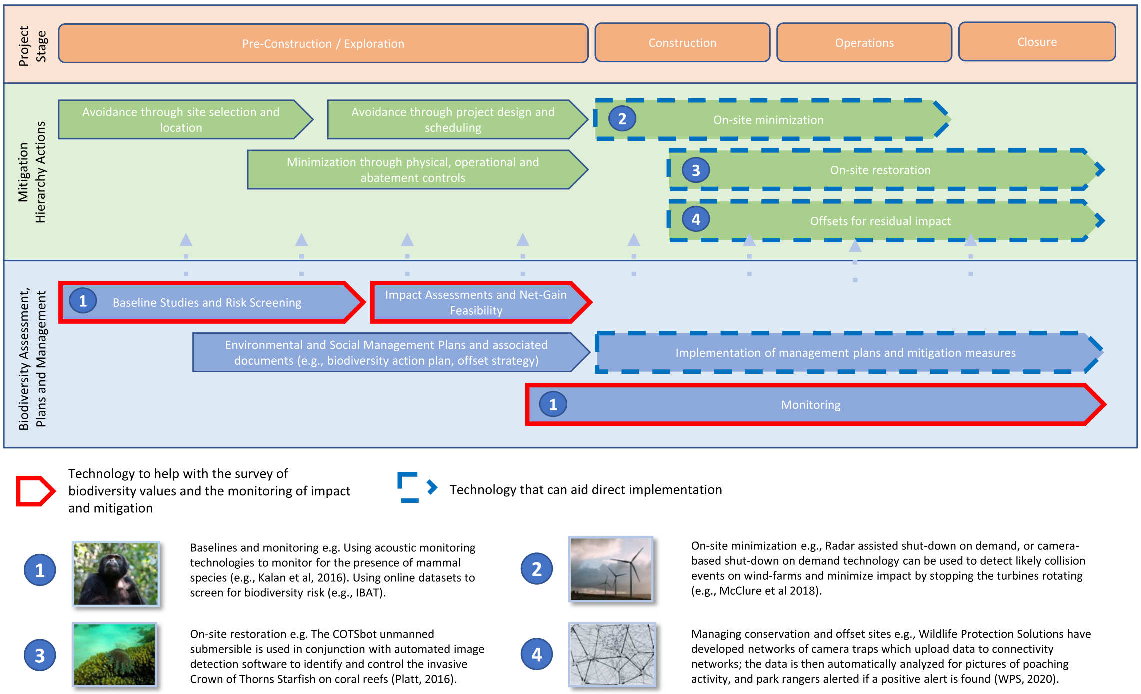

FIGURE 4 Diagram of technology application at different MH steps and project cycle stages. Throughout the project cycle (orange) technology can aid in the design and implementation of many mitigation hierarchy actions (green). This can be through allowing and improving direct implementation of those measures, or through enhancing the delivery of biodiversity-relevant assessments and activities (blue) which feed into the design and implementation of those actions [Colour figure can be viewed at wileyonlinelibrary.com]

(Marvin et al., 2016), some applications still require specialist expertise for bespoke construction or modification.

In the future, advances in battery life and data storage are likely to continue, enabling units to collect data over longer time periods without being recharged or retrieved. Combining technologies may also improve efficiency, for example, by using UAVs with Bluetooth capability to collect and transfer data automatically from GPS tags (e.g., Cliff et al., 2015), or using internet connectivity and artificial intelligence (AI) to upload and/or analyze data from sites in near-real time (e.g., Corcoran et al., 2019; Fijn & Gyimesi, 2018; Global Fishing Watch, 2019; Wall et al., 2014).

2.1.2 | Fixed place survey

An array of innovative survey technologies where data are collected in a fixed location—including camera traps, eDNA, and passive acoustic monitoring (PAM)—can also improve the technical and cost-efficiency of baseline and monitoring surveys. Similar to mobile survey technologies, this increased understanding is important for the design of appropriate mitigation measures and for monitoring their effectiveness.

Camera traps, equipped with traditional, infrared, or thermal camera and video technology, are now commonly used and adapted for a wide range of species and purposes (Marvin et al., 2016; Moore & Niyigaba, 2018; Williams et al., 2014), including underwater (Williams et al., 2014) and for surveillance of illegal activity (Marvin et al., 2016). Similarly, PAM devices can allow continuous non-invasive surveys of species' presence (e.g., Kalan et al., 2015, 2016; Marcoux et al., 2011), including those hard to detect with traditional surveys (Dufourq et al., 2021; Jaramillo-Legorreta et al., 2017; Moore & Niyigaba, 2018), collecting data to monitor activity (Wrege et al., 2010; Wrege et al., 2012), estimate population sizes (Oppel et al., 2014), track threatening processes such as illegal logging or blast fishing (Braulik et al., 2017), and monitor soundscapes as a proxy of habitat quality (Merchant et al., 2015). Techniques to sequence the DNA present in environmental samples (e.g., surface soil, freshwater, and seawater) allow determination of species' presence (including highly cryptic species; Akre et al., 2019) through a quick, non-invasive, and easily standardized approach (Barsoum et al., 2019; Thomsen & Willerslev, 2015) (Figure 3). eDNA technology is also being developed for meta-barcoding to determine the biological community and develop measures of habitat quality. For example, Cordier et al. (2019) use eDNA meta-barcoding to look at the impact of offshore gas platforms on benthic and planktonic eukaryotes.

Fixed survey technologies can also be used to minimize impacts on particular species or groups of species during construction or operations. At wind farms, radar- or camera-based sensors can detect potential collision events for priority bird species and trigger shut-down of the turbines posing risk, either in support of human observers or as a fully automated process (e.g., McClure et al., 2018; McCLure et al., 2021; Tomé et al., 2017; Figure 4). The technology is applicable elsewhere, for example, for airports, and can also be used for baseline assessments of bird movements, for example, FlySafe Bird

Avoidance Model (Dekker et al., 2008) and BirdCast (Cornell Lab of Ornithology, 2020).

Fixed survey technologies are widely available and feasible to use. A broad range of camera traps are commercially available, and they are generally inexpensive and require no specialist expertise (Marvin et al., 2016; Williams et al., 2014). PAM devices are becoming more cost-effective in both marine (Merchant et al., 2015) and terrestrial environments (Farina et al., 2014). Sensors are becoming smaller, cheaper, and less power-hungry, and a range of commercially available microphones are available for terrestrial settings (Farina et al., 2014). Lastly, eDNA sampling is simple and easy, with the sequencing carried out by specialized commercial laboratories.

Automated species detection products are also available from several commercial organizations and are affordable for many industries, although units are currently bespoke and expensive compared to other technologies. Camera and radar-based detection systems have differing strengths and weaknesses (e.g., species classification, distance of detection, and sensitivity to weather conditions), but future advances are expected from combining these technologies, using radar for initial detection and cameras with AI for species identification (where many free packages are being developed for analysis; see Section 2.1.5 below). The technology can also be combined with GPS tags (e.g., a geo-fence can be created which automatically shuts down adjacent turbines if crossed by a tagged condor; Sheppard et al., 2015).

However, all technologies above can present specific challenges. Camera traps are limited in their detection distance compared to traditional surveys, and PAM devices can require specialist data analysis expertise or time-intensive manual data analysis to identify calls and build reference datasets (Merchant et al., 2015). For eDNA, current challenges relate to gaps in reference DNA databases, poor applicability to some taxa at present (e.g., plants), challenges in picking up DNA that is not spatially and temporally explicit, and the need to transport samples internationally for processing. In all cases, a major hindrance is that these technologies produce very large datasets that are challenging to analyze.

Ongoing advances in detection and classification algorithms, and in reference databases, are likely to enable huge improvements in the speed, cost, and quality of analysis, allowing near-real-time analysis of large datasets from camera traps and PAM (see Section 2.1.5 below). Advances in eDNA are expected through rapid improvements in the taxonomic and geographic coverage of reference databases, and developments in meta-barcoding, technology able to determine species' abundance as well as presence (Parker, 2019), and handheld genetic sequencing devices to allow in-situ analysis by survey personnel.

2.1.3 | Remote sensing

Satellites monitoring the earth's surface can inexpensively and easily provide a range of landscape-scale environmental data, reducing the need for potentially costly, invasive, and hazardous fieldwork activities. Recent data are often immediately available, enabling risk screening early in project planning and effective avoidance of high-risk areas. Satellite imagery can also support the implementation and monitoring of mitigation measures throughout the project cycle, for example, in restoration and offset activities by guiding site selection, producing high-resolution digital elevation models, quantifying vegetation type (i.e., restoration success) and levels of fire risk (Cordell et al., 2017).

Satellite imagery has evolved from an expensive, niche product used only by the largest institutions, to a technology that is widely and routinely applied by projects for both environmental and non-environmental purposes. Datasets are now available at a global, national, and local levels (e.g., LandSat imagery, Global Forest Watch, Google Earth) and can be used to assess habitat types, vegetation dynamics, biomass, climatic and meteorological variables, surface temperature, moisture, and CO_2 flux (Marvin et al., 2016). Many of these datasets are easily accessible through software such as ArcGIS and Google Earth and free to access (e.g., LandSat, Sentinel imagery) including almost all NASA-sponsored imagery (Marvin et al., 2016).

Newer approaches such as LIDAR (Light detection and ranging), which uses pulsed lasers to measure distances, and hyperspectral imaging, which analyzes a wider spectrum of light, allow the collection of information on vegetation structure, for example, canopy height, biomass, and vertical stratification (Lee et al., 2015; Marvin et al., 2016) (Figure 3). The resolution and spectral width of available imagery continue to increase.

New satellite constellations allow near-real-time monitoring of the earth's surface (Pimm et al., 2015). Tools such as FIRECAST and FIRMS already provide information on fire outbreaks, deforestation, and droughts in near-real time, and weekly GLAD (Global Analysis & Discovery) alerts identify deforestation events on a 30 × 30 m scale (FIRECAST, 2019; Hansen et al., 2016). Through these tools, projects can collect timely information on the status of habitats, levels of degradation (e.g., deforestation, fire, and erosion), or illegal activity at project and offset sites. Such datasets will likely become increasingly available in the future. For example, there are plans to launch near-real-time monitoring systems for the world's coral reef habitats (Butler, 2018). Caveats do remain, for instance some commercially produced and high-resolution datasets remain prohibitively expensive (Marvin et al., 2016), although the development of constellations of small, low-cost satellites (e.g., CubeSats) may lower data costs in the future (Pimm et al., 2015).

2.1.4 | Blockchain

Blockchain is a public digital ledger system that is distributed widely across many computers so that records cannot be altered retroactively without altering all the subsequent units in the chain (Baynham-Herd, 2017). Blockchain technology can be used by organizations to track and verify the environmental credentials of products in supply chains to show where mitigation measures have been effectively applied (Figure 3). Offsets and compensation programs could use blockchain to track environmental goods produced on managed areas of land or sea (e.g., if preventing forest loss through alternative livelihood programs, goods that are "biodiversity" friendly could be certified and traced through blockchain; Baynham-Herd, 2017). Blockchain can help to verify that landowners are meeting environmental agreements and provide a basis for processing compensation payments in offset and compensation programs, particularly useful in areas of unstable governance (Sutherland et al., 2017).

The use of blockchain for environmental applications is increasing. Le Sève et al. (2018) identify 65 such initiatives, although many of these are at a pilot or research stage. At present, blockchain solutions can be expensive and difficult to implement institutionally but are developing rapidly in other sectors. Future developments that could improve site management for conservation include the use of smart blockchain-based contracts to monitor environmental performance, and cryptocurrencies for systems of environmental valuation (Le Sève et al., 2018).

2.1.5 | Data processing

Technologies to store, distribute, and process environmental data to produce and disseminate useful information have advanced rapidly over the last few decades and are at the heart of improvements in mitigation. Online databases of protected areas, areas of important habitat, species abundance, ranges, and threats (e.g., IUCN Red List, Key Biodiversity Areas, DNA libraries [e.g., The Barcode Library and GenBank], MoveBank, the Global Biodiversity Information Facility [GBIF], and Tropicos botanical data) are being constantly improved (Pimm et al., 2015). These datasets can inform decision making at multiple project stages, for example, by focusing baseline surveys and shaping early stage mitigation measures (Bennun et al., 2018; IUCN, 2014). Databases are also available to help practitioners identify likely biodiversity impacts and dependencies (e.g., ENCORE) and to choose effective interventions (e.g., Conservation Evidence; Nature Based Solutions Evidence Platform). Many environmental databases are freely available online or for commercial use via subscription (e.g., the Integrated Biodiversity Assessment Tool [IBAT] that brings together several key global databases for project screening and mitigation planning).

Data processing, including artificial intelligence (e.g., high-level pattern recognition and deep learning technologies), has dramatically advanced over the last 10 years (Sutherland et al., 2016). Technology is now available for the automated detection and classification of species and habitats within imagery and audio recordings, helping overcome the problem of analyzing large amounts of data collected through fixed or mobile survey technologies (Klein et al., 2015) (see sections above). Algorithms can already classify camera trap images of birds and mammals; identify habitat types in remote sensing imagery (Chen et al., 2014; Norouzzadeh et al., 2018); classify audio recordings of bat, elephants, primates, and bird vocalizations; and help to detect rare species in audio recordings, monitor populations through time, and detect invasive species (Dufourq et al., 2021; Heinicke et al., 2015; Klein et al., 2015; Maina, 2015; Walters et al., 2012). For example, Norouzzadeh et al. (2018) used networks to count, identify and describe behavior of 48 animal species in 3.2 million images from camera traps—saving approximately 17,000 h of human labeling of the images. So far, research has focused mainly on a small set of well-known taxa but is expected to expand in scope as reference databases improve.

An increasing number of apps and tools are also available to help with the collection and analysis of survey data in the field. Software packages allow in-field data collection and visualization of location, satellite imagery, and GPS coordinates of previously collected information (Joppa, 2015). Examples include ESRI's Spatial Monitoring and Reporting Tool and SMART software for protected area and site management (SMART, 2017). Some tools demonstrating AI for environment application are already available to aid data collection in the field and process visual or audio datasets such as Wildlife Insights (Figure 3), iNaturalist, Warblr, iBatsID, and Merlin. However, this is an active area of research and tools are often at the research stage, limited to a few well-known taxa and geographies, and accuracy of outputs can be variable.

Rapid advances are expected in this field with the continued improvement of online databases, detection and classification algorithms (and associated reference databases), and cellular connectivity to allow devices to be used in the field (see Section 2.1.6 below). This will offer potential for near-real-time analysis of species presence or threats to improve the mitigation of biodiversity impacts during construction and operations.

2.1.6 | Enabling technologies

Enabling technologies are defined as technologies that facilitate the delivery and functioning of other technologies. Therefore, they can promote the use of innovative technology for mitigating impact and indirectly enhance technology use in baseline and monitoring surveys—providing data to improve the efficiency of mitigation measures. For example, developments in battery technology have greatly increased the field use of survey equipment such as GPS tags, mobile devices, and UAVs (Bicknell et al., 2016; Kelling, 2018; Sheppard et al., 2015). Continued advances in the storage abilities of batteries (Sutherland et al., 2017), combined with decreasing power demand, will be a key factor in expanding the use of many of the technologies listed above.

The rapid expansion of mobile telephone networks (including 3G to 5G connectivity), GPS networks, and internet coverage (Maffey et al., 2015) is also enabling other technologies. Mobile networks now cover many areas of the world and are increasingly cheap to connect to. These networks support the use of technology deployed at all MH stages—allowing access to software and databases, facilitating data collection and storage, and making near real time data analysis a possibility. Although not all technologies or databases are routinely accessed remotely (see Section 2.1.5 above), access to satellite imagery, detailed mapping, and identification databases are some examples where phone networks can valuably support biodiversity surveys in the field. In 2017, there were over 8 billion mobile devices globally, almost half of which were smartphones and tablets, and large increases in annual global mobile data traffic, with highest rates of increase in the Middle East, Africa, and the Asia-Pacific (CISCO, 2019). The availability of phones and tablets has enabled development of apps for field survey and data analysis (e.g., SMART, iNaturalist; see Section 2.1.5 above). They also facilitate communication among staff and stakeholders, improving both safety and environmental outcomes. However, gaps in network coverage do remain, especially in remote areas.

Combining communication networks with data analysis and sensor technologies offers potential for fast automated transfer of environmental information. The "internet of things" extends internet connectivity into sensors and devices, with potential benefits across the MH as multiple technologies can be linked into these networks—allowing real time monitoring and response to the situation on sites (e.g., Guo et al., 2015). For example, whole systems have been developed at conservation sites to monitor and automatically respond to illegal activity and even to monitor individual animals' health (e.g., Hodgkinson & Young, 2016; NEC, 2018; Figure 4). Further work is needed to improve the feasibility of businesses scaling up such approaches. Sensors are rapidly decreasing in price, but 'off the shelf' technology is not yet adaptable to a wide range of project contexts.

3 | INTEGRATING TECHNOLOGY INTO THE MH

Based on our literature review, in-depth interviews, and associated analyses, we identified a set of 24 technologies with potential for application at all stages of the MH. In particular, these technologies can support businesses to better understand baseline values, and to predict and monitor impacts. In some cases, they can directly help to reduce and compensate for impacts (Figure 4).

These technologies have broad applicability and are affordable, well developed, and attracting significant commercial interest. Through providing data to improve the early consideration of biodiversity risk, they have considerable potential to strengthen the avoidance stage of the MH, which is crucial to achieving NNL/NG goals (Phalan et al., 2018; Sonter et al., 2020). Survey and monitoring technologies can also help to guide and monitor mitigation implementation and outcomes at other stages of the hierarchy, refining the implementation of avoidance, minimization, and compensatory actions. Some technologies (e.g., UAVs for seedling restoration, collision identification technologies, and blockchain) offer innovative techniques for businesses to minimize, restore, or compensate impacts (Figure 4).

Although technology can help implement measures throughout the MH, in practice, such efforts are intertwined with technical and practical difficulties (e.g., Maron et al., 2016). For example, avoidance measures are often not considered or considered too late in project design to be meaningfully applied (Jacob et al., 2016; Phalan et al., 2018), or there may be a lack of biodiversity-related knowledge or environmental mandate at a business to appropriately measure impacts or design effective mitigation strategies (e.g., Bhattacharya & Managi, 2013; Globalbalance & The Biodiversity Consultancy, 2014). Where measures are designed, there may be a lack of monitoring to ensure success after implementation (Tischew et al., 2010). Taking offsets as a specific example, there are often technical challenges quantifying impacts to biodiversity, or determining whether or not impacts can be offset (Bull et al., 2013; Pilgrim et al., 2013), and practical challenges during implementation such as changing regulations, lack of stakeholder support, or lack of skills or capacity (e.g., Brownlie et al., 2017; White et al., 2021). Technology cannot solve these issues, but it could be an important tool in helping improve the success of measures in practice. For example, using technology to improve the efficiency of baseline surveys and monitoring can help alleviate problems of capacity and resources. As another example, the availability of new, bigger datasets from baseline surveys does not necessarily lead to be more effective avoidance and minimization, but by having these datasets, it removes one barrier to implementing these measures on the ground.

4 | CHALLENGES AND OPPORTUNITIES

There are several challenges and (often related) opportunities for implementing these technologies to support NNL/NG goals:

- Implementing, improving, and developing technologies—Our review identifies technologies with potential to improve the effectiveness and cost-effectiveness of biodiversity management. Many technologies are sufficiently developed for immediate application, and we recommend that businesses start using these technologies in their biodiversity management operations where possible and provide resources and collaborative opportunities for further development and research.

  Application of other technologies is currently limited by the expense and specialized expertise required for bespoke implementation. Commercially available tools that are cost-efficient and easy to use would reduce these constraints (Lahoz-Monfort et al., 2019). There is an opportunity for industry actors to work proactively and collaboratively with researchers, conservation NGOs, and engineers to catalyze the development of commercially viable tools (Iacona et al., 2019; Joppa, 2015).

  With diverse operations and a long history of fostering technological innovation, the private sector is in a good position to link the conservation community with expertise in other disciplines. Collaborative platforms such as WILDLABS can help to promote discussion across sectors and disciplines, disseminating good practice, linking technology groups together, and matching technologies to particular industry needs. They can also promote industry sharing of environmental data, via online platforms such as GBIF, to help reduce current data gaps.

- There have been calls for the creation of an international organization or multi-stakeholder network to provide leadership and vision for the development of widely applicable conservation technologies (Lahoz-Monfort et al., 2019). The private sector could play a key role in such a structure, providing resources and expertise and spear-heading development of technologies for biodiversity management in the same way that it has often done for other operational areas.
- Increasing industry capacity and knowledge—Our interviews highlighted that businesses may not have sufficient knowledge, capacity, or perceived need to implement new technologies for biodiversity mitigation. To capitalize on the opportunities provided by new technologies, it is vital to overcome these constraints. By collaboratively working with industry leaders in collaborative platforms, as outlined above, the conservation community can help develop practical guidance and showcase the value of technology use through good practice examples. Industry can take many practical steps to improve their ability to manage biodiversity risk, including recruiting and training appropriately skilled staff, trialing and testing technologies, and developing collaborations to learn from others (e.g., training programs, biodiversity workshops, industry forums, and partnerships with NGOs and research institutions).
- Capitalizing on synergies among technologies—Combining technologies can provide synergistic benefits for biodiversity management. Enabling technologies such as battery power and mobile networks significantly enhance the feasibility and value of using other technologies (Figure 4). Artificial intelligence enables classification and analysis of very large datasets generated by fixed or mobile survey devices. Many other synergies are possible. For example, using remote sensing data from new satellite constellations with online databases of biodiversity information or combining eDNA with bioacoustics and remote sensing datasets in baseline studies to increase the breadth of biodiversity that is covered (Bush et al., 2017). It seems likely that future advances will be made from the combination of currently disparate technologies.
- Broadening application beyond survey and monitoring—As opposed to survey technologies, we identified relatively few technologies for the direct minimization and restoration of compensation of impacts. At present, many of these technologies are relatively costly and/or undeveloped and hence less feasible to implement than survey and monitoring technologies. They may also have narrower applicability, because they are more specific to particular sectors, species, or issues—raising the possibility that these solutions are not fully captured by our study which excluded sector-specific technological solutions. Efforts should be made to develop and improve technologies for direct mitigation, as they can offer innovative solutions to mitigate impacts from different industries.
- Recognizing limitations in technology use—To be useful, new technologies need to be deployed appropriately, building on sound data and analysis, and with careful identification of risks and the effectiveness and costs of potential mitigation measures. Significant human input remains essential. Individual practitioners will need to understand and interpret the biodiversity information available to them and make value judgments about the different biological components, acceptability of impacts, and judge levels of uncertainty in baseline and monitoring information. Technology is a tool to support biodiversity management, not a stand-alone solution for all biodiversity-related problems. Businesses also need to be mindful of ethical implications when deploying novel technologies, including questions of security, data privacy, and legality (Sandbrook, 2015). Careful weighting of the benefits and impacts of use of any technology will need to be done collaboratively and in conjunction with communities and other stakeholders.

5 | OUTLOOK

To achieve global goals for biodiversity (to be agreed in 2021 by Parties to the Convention on Biological Diversity [CBD]) will require transformative change and concerted societal effort (CBD, 2020; Leclère et al., 2020), particularly in light of the current coronavirus pandemic. At the interface between biodiversity impacts and development, the private sector has a vital role to play—with the MH a key mechanism for improving biodiversity outcomes (Arlidge et al., 2018; Milner-Gulland et al., 2020). Conservation technologies have made great advances in recent years, but further work is needed to fulfill their potential for large-scale application by business to support global conservation goals. The conservation technologies highlighted in this review are relevant to private sector operations in diverse sectors and across all steps of the MH and project stages. Thus, they are good candidates for further development effort. Together with conservation organizations, the private sector can help advance technology for biodiversity management—through investing in research, providing user-led input, convening collaborative processes, and leveraging technological developments from other operational areas. This scaling up of research and implementation, alongside the many other efforts needed to address the biodiversity crisis, is urgent but eminently achievable.

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AUTHOR CONTRIBUTIONS

Conceptualization and methodology were performed by T. W., L. V., G. C., C. E., and L. B. Investigation was done by T. W., C. E., L. V., and G. C. Writing of the original draft was carried out by T. W., L. V., G. C., C. E., and L. B. Supervision was done by L. V., G. C., and L. B.

CONFLICT OF INTEREST

During the project, T. W., G. C. and L. B. received income from commercial consultancy services related to biodiversity mitigation in the private sector.

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SUPPORTING INFORMATION

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