From:	Pamela Bartley
To:	SIDS
Cc:	Pamela Bartley
Subject:	RE: An Coimisiún Pleanála Knockshanvo Windfarm: ABP-320705-24 & Grid Connection: ABP-320727-24
Date:	Monday 3 August 2026 21:15:46
Attachments:	Hydro-G Knockshanvo Windfarm ABP-320705-24 & Grid Connection ABP-320727-24 030826 A.pdf

Dear Sids

Please find attached my submission in relation to Knockshanvo Wind Farm planning and the correspondence i received from your office on the 23rd July 2026 in relation to ABP-320705-24. I note the letter from ACP dated the 23rd July 2026 clarified that my response must be received by the Commission not later than the 5th August 2026.

All the best

Pamela

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3rd August 2026

RE: An Coimisiún Pleanála Knockshanvo

Windfarm: ABP-320705-24 & Grid Connection: ABP-320727-24

I am making this observation in response to the Further Information and associated Responses to Observations submitted by FuturEnergy Knockshanvo DAC ("the Applicant"), part of FuturEnergy Ireland in respect of the proposed Knockshanvo Wind Farm. I previously made observations on this file in February and October 2024. I am writing this communication for An Coimisiún Pleanála's public file for case reference Windfarm: ABP-320705-24 & Grid Connection: ABP-320727-24. My Statement of Expertise was presented in the Hydro-G 2024 communications on the file. I respectfully request that An Coimisiún Pleanála considers the details in the previously submitted Observations by Hydro-G and I assert that the information previously presented is factually correct and in no way misleading. I assert that the proposed development is not justified and that the risks are completely understated by agents for the applicant, as is usual for the EIAR industry associated with 'renewable energy', and justification is heavily reliant on 'mitigation'.

The applicant's agent's 'Response to Submissions suggests that a thorough assessment was completed. It was not. The information presented to An Coimisiún Pleanála relies on opinions rather than site evidence. There is a repeated reliance on 'mitigation measures' put forth as reasoning to support the proposed development. An Coimisiún Pleanála is well aware of the legal precedents in relation to 'mitigation measures'. However, the facts of the matter remain that the applicant has presented no mitigation measure for the potential outcome that the proposed construction effort could affect the hydrology of Gortacullin Bog NHA, which is specifically precluded in the Statutory Instrument protecting Gortacullin Bog (S.I. No. 434/2005). Ireland has 148 to 155 statutorily designated Natural Heritage Areas (NHAs) compared to 630 **proposed** Natural Heritage Areas (pNHAs). NHAs are generally restricted to raised and blanket bog habitats (with legal protection under the Wildlife Amendment Act 2000). In County Clare, there are 13 to 14 statutorily designated Natural Heritage Areas (NHAs) relative to 61 pNHAs. Interestingly, 2 Statutorily protected NHAs are within the Zone of Influence of the proposed development: Doon Lough NHA and Gortacullin Bog NHA. Why did the Geographical Information Systems (GIS) of the agents for the applicant not identify that the proposed development area was unsuitable?

The information presented for the applicant is misleading. The EIAR is not sufficiently robust. The Site Investigation programme is from extensive. It is not universally true that best practice mitigation measures ensure the protection of the receiving environment. It is also not universally true that similar mitigation measures have been successfully applied during the construction of countless wind farm developments across the country. When will accountability be applied? The most high-profile Wind Farm case combination of the team advocating a wind farm in proximity to Gortacullin Bog NHA and Broadford PWS Boreholes are the same team responsible for the assessments at Meenbog Wind Farm, in which the EIAR's conclusion of No Potential for Impact was proven incorrect when the land did slide in November 2020 and there was both water impact and habitat destruction requiring Donegal County Council to secure an order prohibiting further works at Meenbog wind farm (Irish Times, April 2024; Donegal Daily, 12th April, 2024). Photographs of the scale of risk for the HES claim of "*Similar mitigation measures have been successfully applied during the construction of countless wind farm developments across the country*" are presented as Plates A & B.

Plate A Proposed Wind farm EIAR author's MKO & HES's previous 'Not Potential for Impact' Meenbog Wind Farm site, which failed in in 2020. (Photo credit Donegal Daily 12th April 2024).

Plate B Proposed Wind farm EIAR author's MKO & HES's previous 'Not Potential for Impact' Meenbog Wind Farm site, which failed in in 2020. (photo credit Donegal Live 4th January 2024).

With specific reference to the scale of watercourse impact shown in Plate A and Plate B, the assessments completed and reported for that Meenbog Wind Farm by the same agents, MKO and HES, are available for review at https://www.pleanala.ie/en-ie/case/300460 and comparison with the information before them now. In 2018 the Board accepted a conclusion by HES (2017) in the Lands, Soils and Geology Chapter that "No significant impacts on the soil and geology of the site of proposed development will occur." and qualifications that "A peat stability assessment undertaken for the site shows that the risk of peat failure is designated trivial and tolerable and that the site has an acceptable margin of safety.". Yet, there was a failure. In the Board's 'Reasons and Considerations' supporting a Grant of Permission for

Meenbog Windfarm the opening statement is that "Having regard to: (a) the national targets for renewable energy contribution of 40% gross electricity consumption by 2020….". However, Mr. Justice Holland is reported by the Irish Times (11th April, 2024) as ruling that "the integrity of the planning and environmental law systems "weighs heaviest" in this case of all the factors in play and favour granting the injunction. He did not see that the "undoubted public interest in wind energy" weighs "much at all" in favour of exercising his discretion against making the order. [Hydro-G provides clarification that Mr. Justice Holland has restrained the developers from finishing their "largely complete" 19-turbine project.] Mr Justice Holland said the developers submitted a report of a civil and environmental engineering expert to the EPA estimating that in the November 2020 incident about 86,240m³ of peat slid, of which about 65,740m³ entered a river and ended up on nearby European-protected sites, "causing significant environmental damage". Hydro-G offers that the Meenbog Windfarm slide of 86,240m³ of peat equates to destroying a carbon sequestration asset equivalent to 14.8 million kgs of CO2 emissions. [Source: National Trust for Scotland, 2024, provides that 172 kg of CO2eq is contained in each m3 of peat]. How much carbon will be emitted here?

It is now well reported in the media that the 'renewable energy' and Wind Turbine industry is contrary to Climate Objectives and the Climate Action Plan. Since 2022, Data Centres have consumed all of the energy that the country has gained from 'renewable energy' infrastructure [1, 2]. The United Nations cites Ireland as a "cautionary tale" for the rest of the world[3]. No longer can the judiciary claim that 'renewable energy' projects are necessary because 'the planet is on fire'. The planet is on fire and this crisis is exacerbated by the business of 'renewable' energy. I attach, as Appendix A to this document, recent academic publications for the Inspector's consideration: the current state of affairs regarding the type of economic endeavor that the wind farm proposal is and how is negatively affects the biodiversity, maladaptation, Ireland's important role in carbon sequestration and the degradation of our landscape.

In the matter of the omission of impact assessment for Broadford PWS's boreholes, the issue is not a small issue and cannot be just dismissed by a 'we didn't mean to leave it out'. No matter whether it was or was not omitted deliberately, nobody is asserting it was deliberate. The issue is the mapped point of contact, a fault or an expansive or compressive geological feature, makes the groundwater supply zone unique to the exact hilltop location of the boreholes and the proposed development area. I have completed an assessment of the hydrogeology of those boreholes. Other locations have been investigated and it is only the exact location of the boreholes that are productive in the context of Public Water Supply scales of abstraction. Whilst Uisce Eireann may generally not formalise objections contrary to government policy, An Coimisiún Pleanála is asked to specifically enquire of Uisce Eireann what the contingency 'Drinking Water Plan' is for Broadford and connected water supply zones in the event of failed 'mitigation measures' for the proposed development.

Separate to water supply, there is the issue of wastewater treatment and the conflict with 'Strategic Infrastructure'. The government charged ACP with renewable energy projects rather than create a specific government department specifically responsible for the roll out of a Government led National Programme of Strategic Infrastructure and Renewable Energy. This has led to the developer-led complicated situation such as the Oatfield & Knockshanvo adjacent wind farm developments combination. The issue here now includes the 'In Combination' effects of the impending construction of Strategic Wastewater Infrastructure serving Broadford and the current omission of consideration of 'In Combination' traffic and the water environment impact potential with 2 wind farms under consideration. Uisce Eireann's commencement of construction of a Wastewater Treatment Plant will result in a discharge to a surface water environment. The 'mitigation measures' proposed for the proposed 2 wind farms has not taken account of the changing baseline for the receiving environment and its assimilative capacity in relation to water quality and biological health.

Hydro-G stands over every reason for refusal presented to An Coimisiún Pleanála in the 2024 Hydro-G Observations and Objections to this and associated adjacent developments. There is no justification for the nature of the proposed development in this landscape. Never mind mitigation, what is the demonstrated contingency plan if the hydrology of Gortacullin Bog NHA is affected? Habib et al. (2024) in Trinity College, Dublin, research opens with "Ireland has > 50% of the EU's ocean-raised bogs; however, degradation through land-use activities has transformed them from carbon sinks to sources. Given their significant role in climate mitigation, it is essential to quantify the emissions resulting from land use degradation of these ecosystems". Gortacullin Bog NHA is RARE in that it actually has a Statutory protection. The agents for the applicant state that there is no risk to affecting the hydrology of the bog because they propose construction downgradient or downslope of the terrestrial ecosystem. However, this is exactly how one makes drainage happen: one excavates downslope. The risks cannot be mitigated. The landscape was never suitable.

Yours Sincerely

Pamela Bartley

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Dr. Pamela Bartley B.Eng, M.Sc., Ph.D

[1] https://www.rte.ie/news/business/2026/0707/1582175-cso-data-centre-energy-figures/
[2] https://www.irishtimes.com/business/2026/07/07/data-centres-account-for-almost-one-quarter-of-irish-electricity-usage-in-2025/
[3] https://unu.edu/inweh/news/environmental-cost-of-AIs-Enrgy-use-carbon-water-and-land-footprints

Appendix A
Scientific Publications Relevant to the Assessment

(a) Locke *et al.,* (2026) opens with *"Human activities are driving a global decline in biodiversity and are interfering with the natural processes essential for human well-being.* ***Achieving climate and development goals is impossible without keeping nature intact.*** *In this article, we establish the urgent need for a paradigm shift toward a "Nature Positive" (NP) future, where the health and resilience of the Earth system are recognized as the fundamental basis for human prosperity. This requires that humanity acts to halt and reverse the loss of nature by 2030." The same paper closes with "It is time for us to recognize that nature is the foundation of all human affairs. Unless we act swiftly to make the world NP by 2030, our lives are likely to become very difficult in a destabilized Anthropocene.*

- Hydro-G offers that the European Union (2024) Regulation Of The European Parliament And Of The Council on Nature Restoration and amending Regulation (EU) 2022/869 sets out on the path towards attempting to achieve a Nature Positive future.

(b) Damiens *et al.,* (2021) opens with "*Economic development is increasingly impacting biodiversity, leading to a rise in biodiversity offset policies globally that aim to compensate for biodiversity losses. Many developments generating offsets create long-term, irreversible losses of biodiversity and, therefore, require biodiversity gains from offsets to be retained over the long term to have any hope of achieving "no net loss" (NNL) of biodiversity. This raises important ecological and institutional challenges that current offset mechanisms, built for politico-economic systems with short-term policy horizons, do not sufficiently consider. We explore this issue and discuss several responses to the problem ranging from incremental changes for improving on-ground management, through to major governance shifts required to support the long-term social-ecological resilience of offset sites. We argue that without these changes, at best, NNL policies participate in temporarily reducing permanent biodiversity loss. At worst, they participate in a false promise, distracting institutions from the transformative changes needed to reverse biodiversity depletion".*

- Hydro-G offers that it has recently well covered in the Irish media that since 2022 none of the renewable energy MWs have been used to assist citizens in reducing their use of fossil fuels. No Climate Action has been achieved. Instead, Ireland is cited as a 'cautionary tale' by the UN in the context of every single MW of renewable energy been given to new industry, thereby countering Climate Objectives.

(c) Habib *et al.* (2024) in Trinity College, Dublin, research opens with "*Ireland has > 50% of the EU's ocean-raised bogs; however, degradation through land-use activities has transformed them from carbon (C) sinks to sources. Given their significant role in climate mitigation, it is essential to quantify the emissions resulting from land use degradation of these ecosystems".* They developed a mapping system "using Sentinel-2 imagery, random forest machine learning and Google Earth Engine" and their results are fascinating and are summarised as follows: *"The results revealed that agricultural grassland comprised 43% of the land use on raised bogs, followed by, forestry (21%), cutover (11%), cutaway (10%) remnant peatlands (13%), waterbodies and built-up ~ 1% each. The overall accuracy of the map was 89%. The map was used to estimate CO2 emissions for four classes constituting 85% of raised bogs: cutover, cutaway, grassland, and forestry using the IPCC wetlands supplement and literature-based emission factors, we estimated emissions at ~ 1.92 (± 1.58–2.27 Mt CO2-C-yr−1) and ~ 0.68 Mt CO2-C-yr−1 (± 0.44–0.91 Mt CO2-C-yr−1) respectively. This is the first study to spatially quantify land use and related emissions from raised bogs. The results have revealed widespread degradation of these globally rare habitats, making them net emitters of CO2. The map is vital for the conservation of these ecosystems through restoration efforts, and the methodology can also be applied to other regions with similar peatland land use issues".*

- Hydro-G offers that the science is abundantly reported and all points to the importance of restoring peatlands such as the areas around the proposed development. It is not enough anymore to greenwash the business enterprise that accompanies the rush to 'renewable energy' in an Irish context. Construction sites with large machinery that will enable turbines to rotate and change air patterns resulting in 'wake' is something that has previously been presented to An Commissiun in many Observations relating to Wind Farm proposals.

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Nature Positive: halting and reversing biodiversity loss toward restoring Earth system stability

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Abstract

Human activities are driving a global decline in biodiversity and are interfering with the natural processes essential for human well-being. Achieving climate and development goals is impossible without keeping nature intact. In this article, we establish the urgent need for a paradigm shift toward a "Nature Positive" (NP) future, where the health and resilience of the Earth system are recognized as the fundamental basis for human prosperity. This requires that humanity acts to halt and reverse the loss of nature by 2030. The Kunming-Montreal Global Biodiversity Framework (GBF) provides a critical roadmap for this NP goal, and global policy increasingly recognizes that environmental targets can only be effective when integrated with global climate, ocean, and human development agreements. This requires a biodiversity conservation approach that accounts for both biotic and abiotic components of the Earth system. We assess the adequacy of GBF targets for stabilizing the Earth system and highlight key gaps. We employ the Three Global Conditions Framework (3Cs), which categorizes landscapes by human impact levels as a practical method for guiding appropriate NP actions, and we extend its application to the marine realm. We outline specific actions and metrics for patterns and processes across all scales needed to achieve biodiversity conservation in synergy with climate stabilization and securing freshwater systems. Our findings emphasize that preventing the loss of intact biomes, ecosystems, and species assemblages is the most critical strategy while acknowledging the urgency of extinction prevention and the need for restoration. Additionally, we highlight the importance of incorporating

Indigenous and local knowledge systems alongside scientific methods to achieve effective and equitable conservation outcomes. Finally, we discuss the need for economic transformation and the private sector's role in fostering an NP future.

KEYWORDS
biodiversity, climate change, Global Biodiversity Framework, Nature Positive, planetary boundaries, Sustainable Development Goals, Three Conditions Framework, indigenous and traditional knowledge

Key points

- Stabilizing the biophysical components of the Earth system requires a unified "Nature Positive" (NP) approach to global environmental goals and governance through greater integration of global agreements for human development, the climate, biodiversity, and the ocean.
- To achieve the NP goal by 2030, the top priority should be preventing the loss of intact biomes, ecosystems, natural processes, and species assemblages, as they are irreplaceable and cannot be quickly restored. At the same time, urgent efforts to prevent species extinction and restore nature remain essential.
- Three Global Conditions Framework (3Cs) serves as a strategic approach to halt and reverse the loss of both the processes (biotic and abiotic) and patterns (species distribution and assembly) of biodiversity, as these are integral components of the Earth system, and to ensure their sustainable use.
- Incorporating Indigenous or traditional knowledge and practices, which are rooted in responsibility to the living world and inherently include awareness of biotic and abiotic processes, is essential to achieving the NP goal.
- The NP shift requires transforming our economic system to work within the Earth system and equitably support human development.

Introduction

Human exploitation of nature driven by prevailing economic systems of production and consumption is causing a rapid and catastrophic decline in biodiversity (1) while simultaneously disrupting the climate system (2). These actions are actively destabilizing the Earth system upon which human health and development depend (3), and the trajectory of environmental degradation is accelerating, placing life as we know it at grave risk.

Biodiversity loss occurs at three interconnected scales—species, ecosystems, and natural processes—all of which affect Earth system stability. At the species scale, 48% of vertebrate and insect species are in decline, with only 49% remaining stable and 3% increasing (4). Within individual species, genetic diversity is also in decline (5): globally, 6% of species are losing genetic diversity, rising to 24% among island species (6). At the ecosystem scale, 54% of the world's ecoregions are severely degraded, with an additional 25% undergoing further degradation, leaving only a quarter largely intact (7, 8).

Natural processes, which encompass both biotic and abiotic interactions across ecosystem, biome, continental, and planetary scales, are also under threat. Migration, a key biotic process essential for maintaining ecosystem health and structure (9), is increasingly imperiled across terrestrial, freshwater, and marine environments. Alarmingly, 44% of species tracked by the Convention on Migratory Species (CMS) are in serious decline, with 97% of listed migratory fish species facing extinction (10). Similarly, biotic and abiotic interactions, also known as biophysical processes (11), are threatened. For example, running freshwater systems, such as springs, streams, and rivers, are critical biophysical processes that sustain the health of both terrestrial and aquatic ecosystems, yet only 30% of river systems worldwide remain free flowing (Box 1) (12). Excessive nutrient run-off from terrestrial sources has created anoxic "dead zones" in estuaries downstream from the world's most densely inhabited areas (13).

At the biome and continental scales, rainfall processes that involve moisture recycling in rainforests are also at risk, with potentially disastrous consequences for species, the climate, and food security (Box 2). At the planetary scale, ocean warming (14–18), acidification (19, 20), and deoxygenation (17, 21) are altering marine ecosystems. These changes are driving mass coral die-offs due to marine heat waves (22–24), weakening the shells of marine organisms due to acidification (25, 26), and threatening marine foundation species (23).

Human-caused species extinction, damaged and collapsed ecosystems, and disrupted natural processes are not only factors of an ecological crisis but also an ethical failure with profound consequences for human health. Biodiversity loss is linked to the emergence and spread of infectious diseases in humans, animals, and plants (27). Declines in species diversity can increase the number of zoonotic disease-carrying species (28), while ecosystem disruption, such as forest loss, degradation, and fragmentation (29), elevates the likelihood of pathogen spillover from stressed wildlife to humans directly (30) or to livestock and then on to humans, as happened with Hendra virus (31). Ecological disruptions have already contributed to outbreaks of deadly diseases, including Ebola, Marburg, and mpox (32, 33). Climate change further exacerbates these risks, intensifying 58% of the 375 known infectious diseases (34, 35).

Zoonotic disease spillover to humans is an ecological process and therefore an ecological problem (33). Despite mounting

BOX 1 Hydrological systems are critical to a Nature Positive future

Preserving and restoring freshwater hydrological systems and habitats is crucial for achieving the "Nature Positive" (NP) goal, the Sustainable Development Goals (SDGs), and climate change objectives.

River systems (especially in tropical and boreal environments) are rich in methane, a potent greenhouse gas, and account for a substantial portion of methane emissions. Disturbing river hydrology releases methane into the atmosphere, with 10% of all global freshwater methane emissions resulting from dams (36). Conversely, maintaining and restoring hydrological processes reduces methane emissions (37).

Another example is peatlands, vital carbon and water reservoirs that depend on intact hydrology. Tropical peatlands store more carbon than upland forests (38), while those in the Northern Hemisphere are spatially more extensive (39). Peatlands release carbon when drained, whether through peat mining or infrastructure projects such as roads, dams, and water diversions (40, 41). Protecting intact peatlands and their hydrological functions is crucial for maintaining their carbon storage capacity and preventing them from becoming carbon sources (42, 43). Rewatering degraded peatlands can serve as a climate mitigation strategy, although its benefits are better understood for northern than tropical peatlands (44). High-elevation peatlands in the Andes (páramos or bofedales) are also essential for water supply in Andean nations (45).

Generally, the deleterious effects of dams are well understood. The Columbia River Basin of North America, with over 40 hydroelectric dams, has seen the near collapse of enormous salmon populations, once numbering up to 100 million returns annually. Functional hydrology is also critical to estuary ecosystems. Mangrove conservation and restoration provide effective nature-based solutions to the climate crisis, as mangroves sequester significant amounts of carbon relative to their area and offer critical shoreline protection and food security (46–48). These ecosystems rely on sediment-bearing freshwater inputs, which are threatened by upstream dams. For example, mangroves in Mexico died off following the construction of dams upstream, whereas those in nearby free-flowing rivers thrived (49). Similarly, hydrological alterations in the Mississippi River delta have caused catastrophic mangrove loss (50, 51).

Therefore, hydroelectric dam removal is a powerful NP action. In the United States, the removal of two hydroelectric dams on the Elwha River has led to rapid ecological recovery, benefiting both marine and terrestrial species (52, 53). Likewise, the removal of four dams in the Klamath River system resulted in salmon returning within 2 weeks (54, 55). In an NP world, more dams would be removed, and new dam proposals would need to undergo a "nature veto", proving they would not harm ecological integrity.

BOX 2 Tropical rainforests—vital Nature Positive actions at the biome level

Maintaining and restoring tropical rainforests of the Amazon, Congo Basin, and Southeast Asia regions is critical to "Nature Positive" (NP) actions owing to their roles in carbon sequestration and storage and the enormous number of species they harbor. The first two also play a vital role in rain generation at the continental scale.

Amazonian rainforest generates a significant part of its own rainfall through moisture recycling (56), but estimates suggest this only occurs if the overall forest cover is 75–80% intact (57). The Amazon Basin is already about 17% deforested (58) and under pressure from global warming (59). Its irreversible transition into savannah-like vegetation would greatly affect rainfall patterns and persistence of the remaining forest and the species it supports (60), as well as the global climate (61).

Modeling indicates that losses of 23% forest cover would put these tropical forest biomes at risk of massive disruption, with potential disastrous effects on agriculture outside their basins (62–65). The Amazon provides rain to the La Plata Basin, the most productive agricultural area in South America (66), and as far away as Texas (67). Loss of this rainfall potentially threatens large-scale food security. Forest cover in the Congo Basin (65) also generates spring rains, with 80% of the atmospheric moisture coming from the transpiration of plants (68). This Central African rainforest is also a major source of rainfall to parts of East Africa (63). Moreover, the Congo is much drier than the Amazon and has larger peatlands—drying of Congo peatlands could the release of a vast amount of stored carbon into the atmosphere (69).

These are more than theoretical concerns. The much-degraded southeastern Amazon has already become a carbon source to the atmosphere (70), and at its southern edge, loss of 55% of the forest is causing nearby agricultural losses due to reduced rainfall (64). According to a recent assessment, human-caused changes in 40% of the Amazon rainforest have moved that part of the system to a bifurcation point where it could exist either as rainforest or savannah (71).

evidence that preserving and restoring nature is the most cost-effective and equitable means of preventing zoonotic spillover (72–74), current public health strategies prioritize biomedical interventions over ecological prevention measures (73). Additionally, the degradation of natural systems has serious mental health consequences, contributing to eco-anxiety among the general population (75, 76) and negatively impacting Indigenous communities whose cultural and spiritual well-being is deeply tied to their environments (77). Conversely, access to nature improves physiological, mental, and cognitive health (78). Recognizing these interconnections, over 200 medical journals jointly called on world leaders and health professionals to address climate change and biodiversity loss as a single, indivisible crisis that must be tackled together to preserve human health and avoid catastrophe (79).

The economic implications of environmental degradation are equally severe. The global economy is embedded in the biosphere (80) and fundamentally dependent on a stable Earth system, which, in turn, is sustained by a healthy biosphere (81). Half of global economic activity, including food production, relies directly on nature (82), and the continuing decline of biodiversity threatens financial stability worldwide (83). The most vulnerable communities suffer disproportionately when nature's ability to provide essential services deteriorates (84).

The very conditions that have made modern human civilizations possible are now unraveling. The Holocene Epoch—the stable, warm, interglacial period spanning the past 12,000 years—enabled the rise of sedentary societies and global development. However, since the mid-20th century, human exploitation of the environment has accelerated, ushering in the Anthropocene, an era in which humanity has become the dominant force driving planetary change (85). We are destabilizing critical components of the Earth system, particularly biodiversity and the climate (3, 86, 87). Our ongoing actions have the potential to push the planet into a new self-reinforcing "Hothouse Earth" state (88), rendering the Earth increasingly hostile to human life (88). Our impacts have placed humanity at such risk that the United Nations (UN) Secretary General has called our collective actions "suicidal" (89).

To provide a coherent and hopeful response to the crisis, international environmental, non-governmental, and business organizations issued a call to the 2020 UN General Assembly to establish a "Nature Positive" (NP) global goal for nature (90). This goal was proposed for use by the Convention on Biological

Diversity (CBD) to complement the UN Framework Convention on Climate Change (UNFCCC) Paris Agreement's carbon-neutral "net-zero" target for climate change and the Sustainable Development Goals (SDGs). In April 2021, NP was formally defined as a goal to halt and reverse nature loss by 2030, relative to a 2020 baseline, to ensure full recovery of nature by 2050 (91). The G7 leaders subsequently endorsed NP as a core objective in their 2030 Nature Compact (92).

The Kunming-Montreal Global Biodiversity Framework (GBF) was adopted in December 2022, and it included the NP global goal of halting and reversing biodiversity loss by 2030 on the way to achieving the GBF's vision of restoring a healthy planet and achieving harmony with nature by 2050 (93). However, this, in isolation, is not enough. It is now widely acknowledged that nature conservation and restoration contribute to climate change mitigation and adaptation and that biodiversity and climate objectives must be addressed together (94–96). Notwithstanding the clear connection, international climate and biodiversity treaties have historically operated in isolation (97).

However, parties have now taken steps toward an integrative approach. The 2023 Global Stocktake agreed at the 28th Conference of the Parties (COP28) to the UNFCCC in Dubai (98) recognized the importance of conserving biodiversity in line with the GBF to achieve the Paris Agreement temperature target. Similarly, the GBF's lack of a clear commitment to support climate goals was substantially remedied by the CBD COP16 Cali decision on biodiversity and climate change in 2024 (99). It calls on CBD parties to maximize potential synergies between biodiversity and climate actions, including prioritization of the protection, restoration, and management of ecosystems and species important for the full carbon cycle. Although efforts to agree on a roadmap to halt global deforestation failed at COP30 in Belem (100), there was greater integration of nature at this climate COP than previously. These important developments are a recognition that both treaties operate in the context of the Earth system.

This article is the first to take an interdisciplinary, intercultural, and integrated approach to examining what is needed to achieve the NP goal on land and in freshwater, as well as in the ocean. Specifically, our analysis focuses on:

- Assessing how NP aligns with the SDGs, Paris Agreement, and GBF and discussing how these existing frameworks could contribute to Earth system stabilization.
- Proposing a holistic NP framework and global-scale metrics spanning all aspects of biodiversity (natural processes, ecosystems, and species) using the Three Global Conditions for biodiversity conservation and sustainable use framework and extending it into the marine realm.
- Recommending alignment of GBF, Paris Agreement, and SDG reporting mechanisms.
- Describing an economic transformation that integrates NP principles while ensuring equitable human development.
- Highlighting the importance of the ways of knowing (sometimes called traditional knowledge systems) of Indigenous peoples and local communities to achieving the NP goal.

Nature Positive and Earth system stability: Sustainable Development Goals, Global Biodiversity Framework, and planetary boundaries

Human development and climate goals cannot be met without a healthy, diverse, and resilient natural world. This section explores these interdependencies and clarifies how the NP global goal aligns with key international development and climate instruments, identifies gaps, and provides a foundation for a more integrated approach to achieve an equitable, nature-positive, and carbon-neutral world.

Nature Positive and the Sustainable Development Goals

The SDGs are a set of biophysical, social, and economic normative goals that seek to end poverty, protect the planet, and ensure peace and prosperity for all by 2030 (101). They have been described as universal, interconnected, and inseparable and are of equal importance, balancing the economic, social, and environmental dimensions of sustainable development (102). Thus, economic goals such as promoting inclusive and sustainable economic growth, employment, and decent work for all (SDG 8) and building resilient infrastructure, promoting sustainable industrialization, and fostering innovation (SDG 9) are placed on equal footing with fundamental human survival needs like food security (SDG 2) and access to clean water and sanitation (SDG 6) as well as environmental imperatives such as climate stability and maintaining life on land and in water (SDG 13, 14, and 15).

When social, economic, and environmental goals are expressed as equal and competing, the SDGs are viewed as seeking the "sweet spot" where they overlap and converge (Figure 1, left side). Fundamentally, this is a conceptual failure: the SDGs may be of equal importance politically, but they are not so in reality.

The Earth system existed for billions of years before humans emerged. Human life, and thus all human development goals, are wholly dependent on the Earth system operating in a way that is favorable to humanity. The various SDGs are simply not of equal importance: those that support the Earth system underpin all human activity (SDG 13, 14 and 15), and humans cannot exist without a conducive Earth system that creates food and water (SDG 2 and 6); the economy was invented by and cannot exist without humans—it cannot thrive unless human society has food, water, health, institutions, and skills sufficient enough to support it (103–105).

Therefore, a more accurate framework acknowledges a hierarchical relationship in which the environment forms the foundation for human society, and the economy exists as a subset of society that must serve human interests (106–108), as illustrated in Figure 1, right side. This perspective aligns with early sustainable development principles that recognized biodiversity, ecosystems, and natural processes as an indispensable prerequisite to sustainable development (103). Addressing the SDGs in that light is now more urgent than ever. The NP paradigm embodies this conceptual shift.

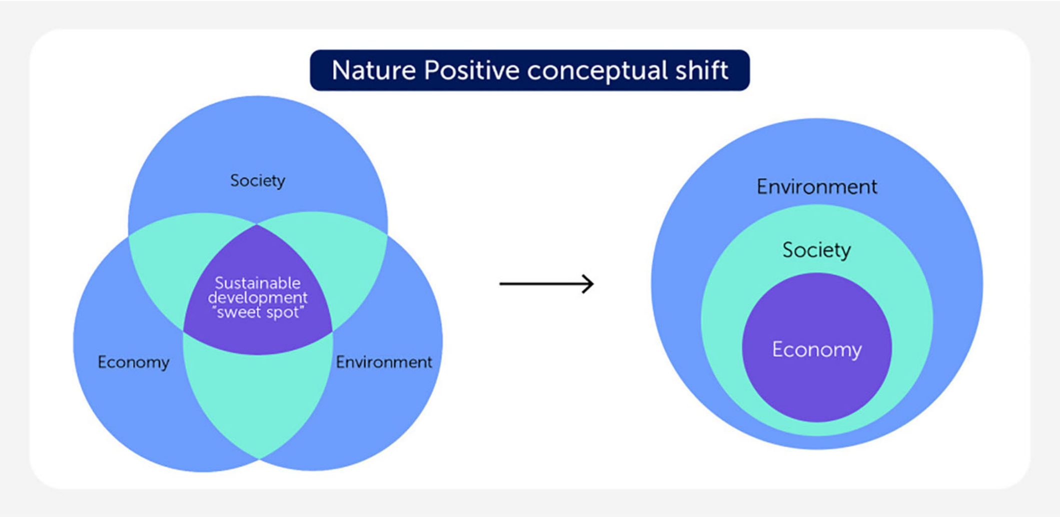

FIGURE 1
"Nature Positive" (NP) involves a conceptual shift from viewing the environment as a competing interest with society and the economy to recognizing it as the context for all human activity. This shift realigns the Sustainable Development Goals (SDGs), moving from the search for the "sweet spot" of overlap between the environment, society, and the economy (left side) to a hierarchical relationship in which the environment is recognized as the context for all aspects of human existence and the economy is understood as a subset of society, existing solely to serve human interests (right side).

Nature Positive and Earth system science

The Earth system comprises the atmosphere, hydrosphere (including the cryosphere), geosphere, and biosphere. The biosphere emerges from interactions among the other three spheres and, in turn, influences them. These feedback mechanisms regulate planetary resilience by buffering stress and shocks (i.e., solar radiative forcing and volcanic eruptions), thereby maintaining equilibrium. The most recent equilibrium state, the Holocene epoch, allowed sedentary civilizations to develop and large human populations to flourish (Figure 2A).

This stable state, however, is now threatened by global human pressures on the Earth system, ushering in the Anthropocene (109). We see more frequent and intensified extreme events (e.g., droughts, floods, heat waves, fires, and disease outbreaks), while we are gradually eroding the biosphere of its life-support capacity, pushing Earth system boundaries toward multiple tipping points (59). Sixteen biophysical and climate tipping points have been identified where self-reinforcing feedback loops threaten to drive irreversible state shifts, ultimately altering the state of the entire planet (Figure 2B) (59). Examples include the transformation of rainforests into savannah-like landscapes due to moisture loss (Box 2), the rapid melting of the Greenland Ice Sheet, and the collapse of tropical coral reef systems.

The Planetary Boundaries Framework emerged from understanding Anthropocene pressures, the risks of crossing tipping points, and the evidence that nature is a precondition for a stable Earth system (110, 111). Nine planetary boundaries that regulate the function and stability of the Earth system have been identified. Humanity's actions have now transgressed seven of them, namely the two core boundaries of biodiversity and climate, together with those for land system change, altered biogeochemical cycles for nitrogen and phosphorus, freshwater change, changes to both blue water (runoff water) and green water (soil moisture), novel entities [human-created chemical compounds, e.g. per- and poly-fluoroalkyl substances (PFAS), persistent organic pollutants (POPs), and microplastics] (3), and, most recently, ocean acidification (112). These crossed boundaries indicate that the Earth is losing resilience and is in a state of internal stress unprecedented in human history (113). In addition, control variables exist but have not yet been quantified for high-seas deoxygenation and ocean heat absorption, which are further exacerbating instability. The Planetary Boundaries Framework is a diagnostic tool providing a dashboard for a safe operating space for humanity on Earth; it does not, however, prescribe solutions or define normative goals (114). NP is the necessary normative goal and pathway derived from Earth systems science that provides a safe landing for humanity within the living biosphere. Combined with carbon emissions reductions, it seeks to return the Earth system to Holocene-like stability by halting the loss of intact nature and transforming nature-negative impacts into nature-positive feedbacks (Figure 2C).

Nature Positive and the Global Biodiversity Framework

The GBF is the primary global agreement that relates to nature and is broadly analogous to the Paris Agreement on climate, although it is not binding in its own right. Both agreements were reached under Rio Framework Conventions (CBD and UNFCCC). The GBF consists of an overarching 2050 vision, an actionable 2030 mission, and specific targets to be achieved by 2030. Its mission is to halt and reverse biodiversity loss by 2030 as a pathway to the 2050 vision of humanity living in harmony with nature, ensuring a healthy planet that provides benefits for all. The GBF promotes cohesiveness and

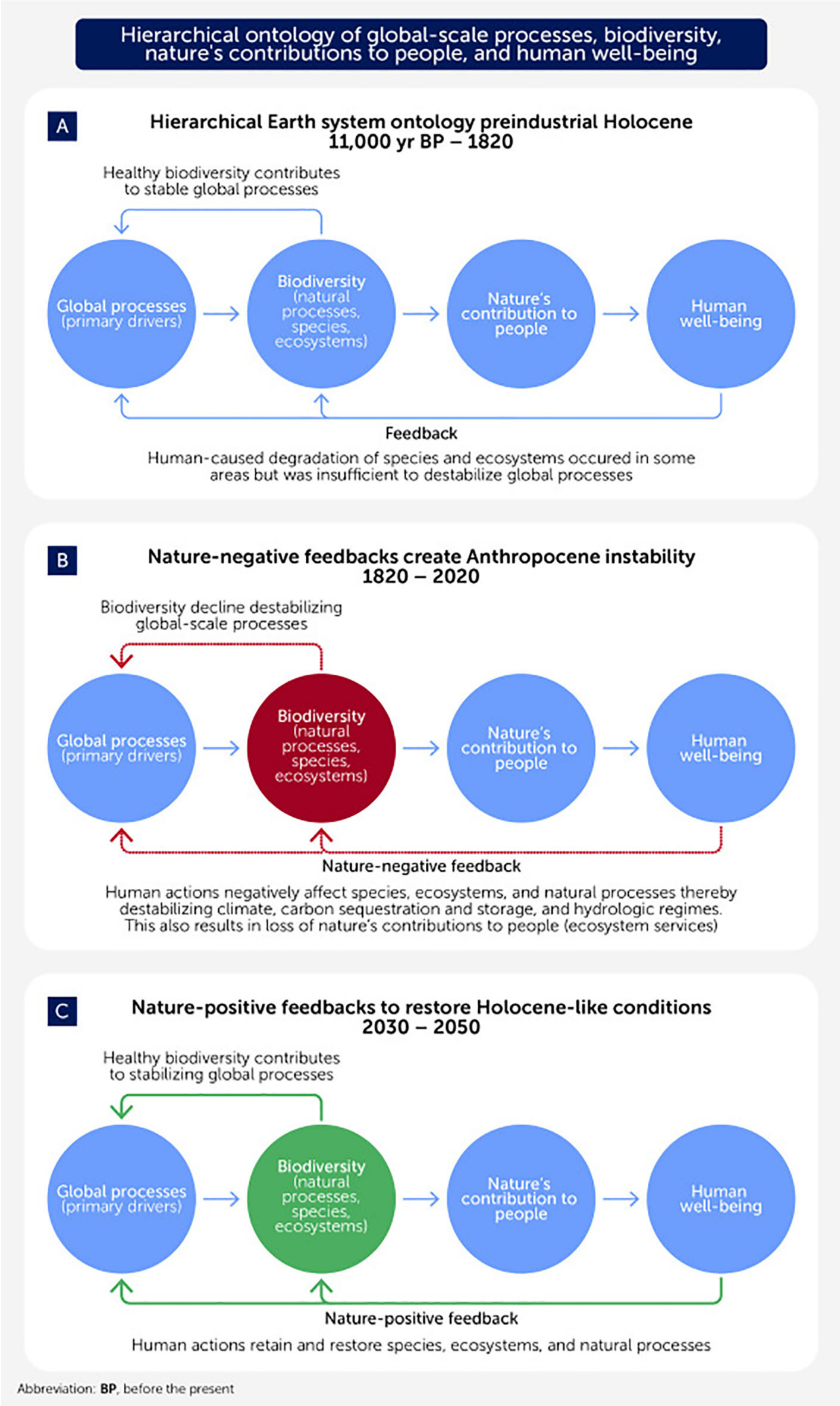

FIGURE 2
Hierarchical ontology of global-scale processes, biodiversity, nature's contributions to people, and human well-being. **(A)** Holocene conditions; **(B)** Anthropocene conditions, during which nature-negative human feedbacks destabilize the Earth system; **(C)** "Nature Positive" actions to halt and reverse biodiversity loss, combined with climate actions to reduce fossil fuel emissions, are needed to restore stable Holocene-like conditions.

complementarity among international agreements (93)[1] and integrates the Rio Declaration on Environment and Development (93),[2] which calls for a global partnership to protect and restore the health of the Earth's ecosystem (115). The GBF also calls for

1 Section B, Global Biodiversity Framework.

2 Section C, Global Biodiversity Framework.

alignment with the SDGs (93) and the One Health approach, which recognizes the link between human, animal, and environmental health (116). To achieve the GBF's 2050 vision, Rio Principle 7, and One Health, we must stabilize the Earth system.

GBF implementation is based on a comprehensive framework that includes monitoring, financial resource mobilization, and an agreement on digital sequence information to support shared benefits from the use of genetic resources. While implementation occurs at the national level through the 196 country parties, the GBF also calls on subnational governments, civil society, business, as well as Indigenous and local communities to participate in a whole-of-society approach.

The GBF's mission of halting and reversing biodiversity loss by 2030 is the NP goal in all but name. Its 2050 goals reinforce this alignment: Goal A calls for the integrity, connectivity, and resilience of all ecosystems to be maintained, enhanced, or restored, thereby substantially increasing the area of natural habitat (93). Goal B calls for biodiversity to be sustainably used and ecosystem functions and services to be maintained and restored. Goals C and D address equitable distribution of benefits, increasing financing, and aligning financial flows with the GBF. While the GBF's goals effectively address many aspects of the 2030 mission, its targets are silent on key elements necessary to meet the GBF's mission, vision, and overarching objective of complementarity with other international agreements. The major shortcoming is a lack of attention to natural processes at all scales. Ameliorating this gap does not require amendment of the GBF, but complementary attention by all actors as discussed below.

Another area requiring focused attention is ocean governance, as there is disagreement over whether the GBF covers areas outside of national jurisdiction, which is almost two-thirds of the global ocean. The Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) under the UN Convention on the Law of the Sea (UNCLOS) is a much-needed complement to the GBF. Its general objective is conservation and sustainable use of marine biodiversity, and it creates a framework for marine protected areas (117). Its specific objectives include building resilience to the adverse effects of climate change and ocean acidification and maintaining and restoring ecosystem integrity, including carbon cycling, in order to underpin the role of the ocean in the climate system. If implemented effectively—through measures such as protecting at least 30% of the ocean and ensuring sustainable fishery management—it could contribute significantly toward the development of an NP world (118). Recognizing this, at the Conference of the Parties (COP16) to the Convention on Biological Diversity (CBD), the Parties decided to "explore opportunities for addressing the ocean-climate-biodiversity nexus in an integrated manner". This integration is urgently required.

Implementing and measuring Nature Positive conservation

In this section, we outline a framework for implementing conservation actions for natural processes, ecosystems, and species, and we present metrics for measuring progress toward the NP global goal.

The scope of the NP global goal was originally described in 2021 as follows:

> *Nature-positive includes a focus on species distribution, abundance, functional traits, genetic diversity, and demographic trends as well as the intactness and integrity of ecosystems and biomes. It also includes the functioning of ecological and global processes such as hydrology, rainfall patterns and migration…. Together these provide a resilient planet able to cope with shocks and stresses without crossing destabilizing tipping points…. Connecting the nature-positive goal to equity and carbon neutrality recognizes the fundamental connection between human development and the health of nature and the deep connection between nature, climate and Earth system stability* (91).

Here, we explore actions and metrics that address the full scope of the 2021 NP global goal. We note a variety of papers published since 2021 that deal with aspects of NP, including an additional proposed metric focused on staying within nature's carrying capacity (119). Useful approaches to measuring biodiversity in terms of patterns and quantification of genes, species, and ecosystems have also been identified (120). However, both biotic and abiotic natural processes must also be addressed to fully conserve biodiversity and contribute to a stable Earth system. We begin with some general principles.

General principles for Nature Positive actions and metrics

To move toward stabilizing the Earth system, the protection of intact nature is our most urgent goal. By "intact" we mean areas free of significant human-induced degradation, which often occur within the territories of local traditional communities and Indigenous peoples (121), and all remnants of primary ecosystems, whether large or small (122–124). Nature restoration is important but secondary to retaining intact nature because any further losses cannot be restored in the critical time we have left. Although tree planting is widely discussed as a climate solution because trees absorb atmospheric carbon dioxide (125), at the global scale, preserving existing intact ecosystems is far more effective for achieving net-zero emissions by 2050 than large-scale afforestation efforts (126–128). This is because most natural systems, when disturbed, lose a substantial portion of their above- and below-ground carbon stores, requiring decades to centuries to recover, which takes us far beyond the 2050 net-zero target (129). Retaining intact nature also maximizes Earth's resilience, which is crucial because climate pressures are already weakening ecosystems' capacity to absorb carbon (130). Remaining intact natural biomes are also vital for retaining rainfall patterns (Box 2), and healthy ecosystems support more species in greater numbers than degraded ones, resist invasive species, reduce pandemic risk (33, 131), and provide greater ecosystem services, such as clean freshwater.

That said, restoration is a primary and urgent strategy in areas of significant ecological degradation, such as New Zealand/

Aotearoa, Western Europe, many Mediterranean-type ecosystems, and in tropical grasslands and dry forests worldwide (132). Reforestation in tropical areas where forest cover has been reduced can rapidly restore some aspects of ecological function (132, 133). Restoration of species composition can improve ecosystem function and help meet carbon-management goals (134); however, this often takes longer than biomass recovery (135). Importantly, reforestation and afforestation are not necessarily synonymous with ecological restoration (136). A singular focus on tree planting for climate mitigation instead of a thoughtful focus on restoring ecosystem composition and protecting native species risks failing both biodiversity and climate goals (137). In two cases, reducing just one human pressure can result in important improvements in species diversity and populations, ecosystem health, and natural processes: (1) discontinuing fishing in ocean areas with minimal human modification (118, 138, 139) and (2) reducing continuous grazing pressure from domestic animals on grasslands that have not yet undergone phase shifts (140).

Establishing baselines is essential for measuring progress (141). The NP global goal is a net improvement in ecological conditions from a 2020 baseline by 2030. The 2020 baseline was set because that is when the last set of conservation targets under the preceding CBD's Aichi Biodviersity Targets expired, and the new GBF was to be negotiated, before the process was delayed by the COVID-19 pandemic. Achieving the NP goal by 2030 does not require every natural process, ecosystem, or species to have improved by 2030. However, it does require that, in aggregate, human actions across the Three Global Conditions Framework (3Cs) have secured the existing intact nature and that substantial ecological restoration actions are underway, so that nature is in better condition in 2030 than it was a decade earlier.

Here, we apply the 3Cs as a practical approach to achieving both the GBF goals and targets and the necessary complementary NP actions that address natural processes.

The Three Global Conditions Framework for implementing the Global Biodiversity Framework and complementary Nature Positive actions

The GBF's targets for actions to protect, restore and sustainably use biodiversity are as follows: reduce loss of intact areas to near zero (T1); restore 30% of degraded areas (T2) and protect and conserve at least 30% of land, freshwater, and ocean in an interconnected way (T3); reduce species extinction risk and curtail unsustainable use (T4, 5, 6, and 9); reduce pollution (T7); address climate impacts on biodiversity (T8); improve sustainable practices for agriculture, aquaculture, wild fisheries, and forestry (T10); and maintain nature's functions and contributions to people or ecosystem services (T11). While the GBF sets global targets that each party will implement in accordance with its own national circumstances (93), it provides no guidance on which of the many required actions apply most effectively in the highly variable conditions that exist among and within countries. For example, while half the world has been transformed by human activity, this transformation is unevenly distributed (142).

Nonetheless, the GBF targets and supplemental NP actions addressing natural processes can be implemented systematically by categorizing the world into three "conditions" of human impact: (1) "Large Wild Areas" with very low human impact (termed Condition 3 or C3, approximately 26% of the terrestrial world), (2) "Shared Lands" ranging from slightly to less than half transformed by human activity (termed C2, approximately 55%), and (3) "Cities and Farms" where land is more than half to entirely transformed (C1, approximately 18%) (Figure 3) (143).

The 3Cs framework has been recommended by multiple expert bodies and institutions, including by: the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Panel on Climate Change (IPCC) as an effective approach to integrating climate and nature actions (95, 144); experts engaged by the CBD as an effective approach to implementing GBF targets in an integrated way (145); African scientists as an effective way to integrate biodiversity targets from local to global levels (146); economists as the most cost-effective means of implementing the 30 × 30 protected and conserved areas under GBF T3 (147); the Dutch Central Bank as an efficient way of reconciling conservation, climate, and food security goals (148); and zoonotic disease experts as an effective way of sorting ecological countermeasures to prevent pandemics (30, 33). It has also been recognized as an approach to support governance that achieves co-benefits alongside social, biodiversity, and climate objectives (149).

For too long, the ocean, freshwater, and land have been treated as separate domains, which has resulted in a fragmented approach to an integrated challenge. For example, no discussion of mangrove conservation is complete without addressing freshwater hydrology and sediment transport (49). Similarly, no effort to remedy oxygen-depleted "dead zones" in marine estuaries is of any value unless it examines harmful terrestrial inputs into freshwater systems (13). Similarly, coral reefs can either be adversely affected by sediments and nutrients from anthropogenic causes or enhanced by background levels of natural nutrients from land (150). Further, the rapid changes in ocean temperature, chemistry, currents, ice cover, foundation species, and fish biomass are cause for alarm. We must therefore pay urgent attention to both reducing stressors and increasing conservation measures across the marine realm. In this article, we seek to remedy the artificial separation of ocean, freshwater, and land by extending the 3Cs approach across all three, allowing for a more holistic and integrated approach.

Human impact on the ocean differs from that on land; the 3Cs approach is not directly transferable except in the case of estuaries immediately adjacent to cities and farms, with C1-level physical impacts (151). However, fisheries-related impacts are analogous to habitat loss on land due to bottom trawling and severely reduced large-bodied fish populations (152–154), which have resulted in ecosystem-level impacts (153, 155, 156). Thus, in the marine context, C1 applies not only to estuaries but also to the 12 nautical mile (22.6 km) territorial waters of most countries, which have been extensively modified by human actions but still retain fragments of semi-intact nature. C2 can be applied to the remainder

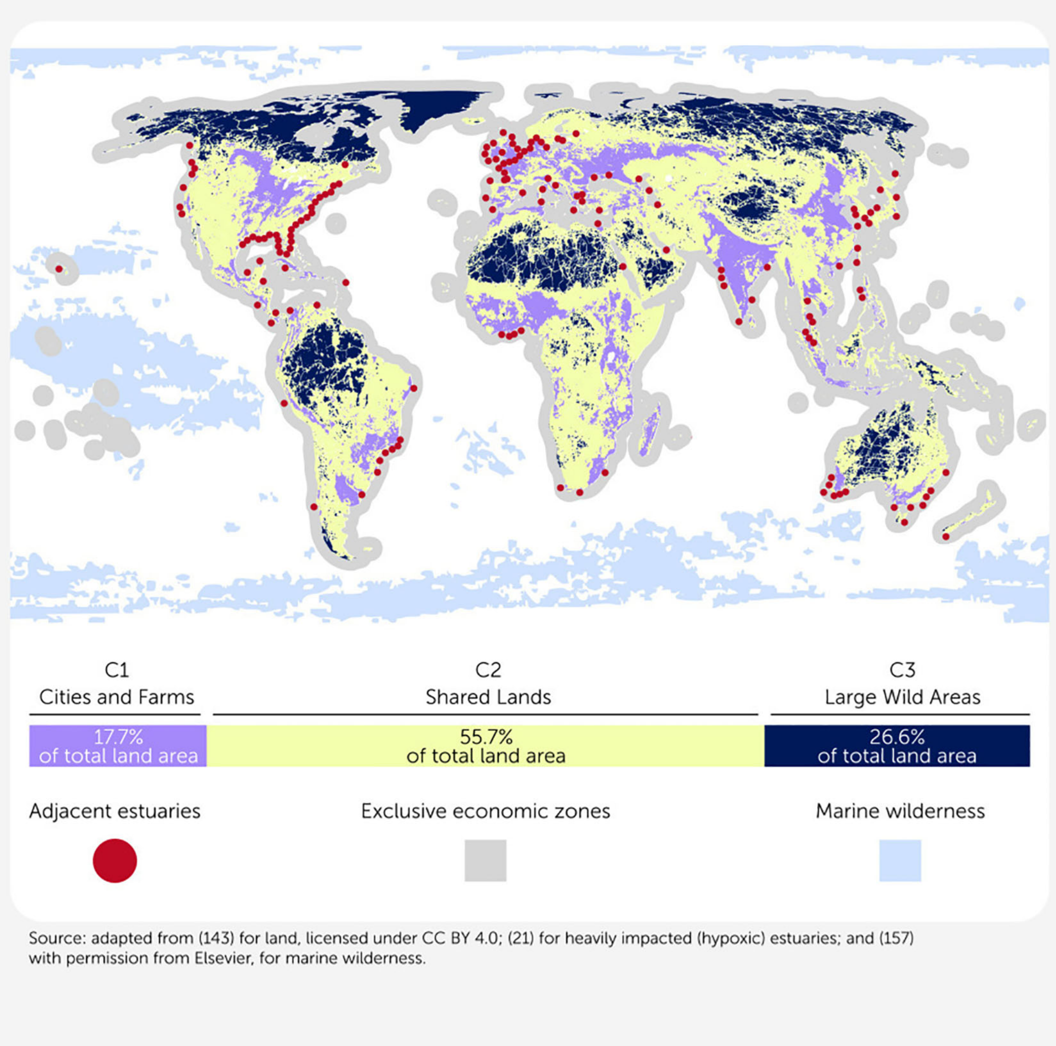

FIGURE 3
The Three Global Conditions Framework (3Cs) for simultaneous conservation and sustainable use strategies applied to land, freshwater, and ocean. Adapted from (143) for land, licensed under CC BY 4.0; (21) for heavily impacted (hypoxic) estuaries; and (157) with permission from Elsevier, for marine wilderness.

of the exclusive economic zones (200 nautical miles) and most of the high seas, where fishing that includes bottom trawling has depleted fish stocks and removed large-bodied fish (152, 155, 158) but where some high-biomass areas with low fishing pressure remain (159). Only the Arctic and Antarctic, which have been protected by large ice sheets, and only the most remote parts of the open ocean (approximately 13%) are "marine wilderness", a condition analogous to C3 large wild areas on land (157).

The 3Cs framework provides a structured approach for implementing NP actions tailored to the human impacts and resulting ecological and biophysical characteristics of each condition (Figure 3). It is not a prioritization scheme but rather provides coherent points of departure for simultaneous conservation and sustainable-use actions appropriate for each condition, because nature matters everywhere.

Maps of the terrestrial 3Cs for every region and country are found at naturebeyond2020.com. We hope this initial integrative work might stimulate more thorough mapping of the 3Cs in the ocean.

Actions and metrics for natural processes, species, and ecosystems

There are well-known and effective strategies for biodiversity conservation, many of which are found in the GBF. Here, we discuss those actions and metrics necessary to measure progress toward the NP global goal and the GBF's vision, goals, and targets across the 3Cs. We also identify gaps in the GBF (Table 1).

Large-scale natural processes

Large-scale natural processes relate to the dependence of ecosystems and species upon, and their interactions with, the abiotic component of the Earth system at scales that affect planetary health and functioning. NP actions targeted at species or specific ecosystem types alone are not sufficient to retain overall structure and function. For example, in large intact areas, GBF species and individual ecosystem targets could be met in isolation, but the entire biome could still collapse. This could result in not only the loss

TABLE 1 Global-scale “Nature Positive” (NP) actions and metrics, and their alignment with Global Biodiversity Framework (GBF) goals and targets, applied across the Three Global Conditions Framework (3Cs) using Conservation Imperatives (160), International Union for Conservation of Nature (IUCN) Red List of Threatened Species (161), IUCN STAR Metric (162), IUCN Green Status (163), and Mitigation Hierarchy (123).

	Actions	Metrics	Goals and targets
C1 – Cities and Farms	**Species level**		
	Conservation Imperative sites are secured	All identified *Alliance for Zero* extinction sites/ Conservation Imperative sites are under effective management to secure the target species	Goal B; Target 3, 6
	All species at risk are in the recovery process	Species moves in a positive direction along the Red List continuum: Species Threat Abatement and Restoration (STAR) metric	Goal A; Target 4
	Connectivity is retained or restored	Some structural connectivity is in place in streams and among terrestrial habitat patches	Goal A; Target 12
	Ecosystem level		
	Retain all patches of native vegetation (land and estuaries)	All patches are inventoried and secured 20% of native vegetation is restored with particular attention to pollinator habitats	Goals A, B; Targets 10, 11
	Superabundant species and exotic species are managed	Exotic and superabundant species are controlled to reduce ecosystem harm and disease risk. New exotic species are controlled quickly	Goals A, B; Targets 6, 12
	Agricultural waste and chemicals (nutrients and pesticides) are kept out of freshwater, streams, and wetlands	No nutrients, herbicides, or pesticides are detectable in freshwater systems	Goal A; Target 7
	There is good urban planning to prevent sprawl and keep the best farmland in production	The best farmlands are retained; there is no increase in area under cultivation	No Goal; Target 10
	Provide people with access to nature for mental and physical health	Equitably distributed, convenient access to green and blue spaces is realized	Goal B; Target 12
	Natural processes		
	There is safe travel for migratory birds and marine life and secure migratory stopovers and nesting sites	All migratory stopover and nesting sites are inventoried and secured Safe travel for birds is increased by reducing collision risk (turning off unnecessary lights in buildings) and controlling domesticated cats Fishing nets are managed to avoid interfering with migratory marine species	Goals A, B; No target
	Hydrological processes are retained and improved; restoration of all four dimensions of freshwater connectivity is carried out as much as feasible	Development on floodplains is halted and reversed where feasible No new dams appear and/or dams are removed where appropriate Seasonal sediment transports return to natural patterns	Goals A, B; No target
	To secure carbon sequestration and storage, all mangroves, seagrasses, and wetlands are retained and restored, and patches of native vegetation are retained (see ecosystem-level actions)	Areas of mangroves, seagrasses, and wetlands increased with good hydrological connectivity	No goal; no target
C2 – Shared Landscapes	**Species level**		
	All species at risk are in the recovery process	Species at risk increased to a minimum population size of 500	Goal A; Target 4
	Missing keystone species are reintroduced	Missing keystone species are assessed and the reintroduction process has begun	Goal A; No target
	Harvest levels do not diminish current patterns of abundance or distribution	A species’ status does not fall below its current Red List status or Green Status	Goal B; Target 4 Red List; No target; Green Status
	Ecosystem level		
		Species levels are assessed for Green Status function and secured; harvest levels are consistent with goals	Goals A, B; Target 9 (partial)

(Continued)

TABLE 1 Continued

	Actions	Metrics	Goals and targets
	All native species currently performing ecological functions remain at current levels of abundance or increased if needed		
	Retain all native vegetation (land and estuaries)	No new areas are cultivated All primary ecosystems are retained	Goal A, B; Targets 1, 3, 8
	Industrial resource extraction (mining, logging, oil, and gas) discharges no sediments out of season or pollutants into watercourses	Water quality, sediment load, and timing are adhered to	Goal A; Target 7 (partial)
	Exotic species are eliminated or controlled Superabundant species are reduced	Exotic species are eliminated to reduce ecosystem harm Superabundant species caused by loss of predation are reduced in number to reduce ecosystem harm New exotic species are controlled quickly	Goals A, B; Targets 6, 12
	Further cultivation is prevented	There is no increase in area under cultivation	Goal A; Target 10
	Ecosystem connectivity and core habitats are secured through an ecologically representative and interconnected system of protected and conserved areas covering at least 30% Protected and conserved areas are managed effectively and governed equitably	Key biodiversity areas are identified Protected or conserved areas, as well as functional connectivity, are present for all species Indigenous and local communities are properly engaged At least 30% of land, freshwater, and ocean is effectively protected or conserved to achieve equivalent outcomes to protected areas, with effective management and equitable governance	Goal A, B; Targets 3, 8
	Gaps in ecosystem connectivity are mitigated	Wildlife crossings are built to mitigate infrastructure (trains, roads, and dams), so functional connectivity is restored There is no isolation of minimum viable populations (500 individuals) from their meta population	Goal A, B; Targets 2, 3, 4
	Domestic animal grazing levels are managed appropriately	There are appropriate stocking rates to maintain good range conditions Domestic animals are kept out of streams and wetlands	Goal A; Target 2
	Natural processes level		
	All migratory breeding and wintering sites, migration patterns within the ecosystem, and continental stopovers are secured	All migratory patterns, stopovers, breeding, and wintering sites are inventoried and secured	Goals A, B; No target
	Large-scale hydrological processes are retained and improved There is retention and restoration of all four dimensions of freshwater connectivity	There are no new dams and there are dam removals Seasonal sediment transport is kept at or returned to natural patterns	Goal A, No target (except Target 2 restoration)
	There is efficient carbon sequestration and storage All primary ecosystems are retained and secured	There is no old-growth logging There is no new cultivation	No goal; no target
	There is sustainable resource extraction	Existing disturbance footprint is the primary focus of operations but where new impacts are unavoidable, the Mitigation Hierarchy framework should be followed and overall landscape context improved	Goal A; Target 10
	Water flow is retained with enough energy and volume to drive ecosystem structure	A minimum of 80% natural water flow is retained or restored	Goal A; No target (except Target 2 restoration)
	Sediment flows follow normal seasonal variability	There is no discharge of sediment from roads, railways, or industrial resource-extraction sites outside of natural seasonality	Goal A; No target

(Continued)

TABLE 1 Continued

	Actions	Metrics	Goals and targets
C3 – Large Wild Areas	**Species level**		
	All abundant species are retained and perform ecological functions	Harvesting rates are consistent with abundance All species are managed to Green Status 3 levels	Goal A; No target
	Species at risk are secured	All species at risk are identified with an action plan toward protection and conservation	Goal A; Target 4
	Ecosystem level		
	All species are able to move in existing natural patterns	There is no new fragmenting infrastructure (new dams, roads, and railways)	Goal A, B; Target 1 (accelerated)
	Ecosystems remain intact	There is no new resource extraction industry (logging, mining, oil, and gas)	Goal A, B; Target 1 (accelerated)
	Natural processes level		
	Biome function is secure	There is 80% tropical forest cover Migrations within biomes and across biomes are possible	Goals A, B; No target
	Hydrological processes are maintained in a wild state	No dams or roads are impacting wetlands or peatlands directly or indirectly There are no water diversions All four dimensions of connectivity are intact There are natural patterns of sediment transport and flooding	Goals A, B; No target

of the species and ecosystems that were intended to be conserved but also of hydrological and biome functions critical to humanity (Box 3).

These large-scale Earth system processes are essential to meeting the GBF's vision of a healthy planet and are implied in Goal B. They are also recognized in the "ecosystem approach" (164), which the GBF states should guide its implementation. However, large-scale natural processes are largely absent from the GBF's targets and indicators. They can be broken down into three categories:

- Abiotic hydrological processes: These are major drivers of ecosystem structure and carbon storage, influenced by biotic feedbacks.
- Intact biome functions: These drive global processes, such as rainfall, through the integrity of biotic and abiotic processes.
- Biotic migrations: These occur at the biome and global scales, are essential for maintaining ecological integrity, and have some abiotic effects.

BOX 3 Action at multiple biodiversity scales: example of the harpy eagle and Amazon Basin

All three interacting scales of biodiversity—natural processes, ecosystems, and species—need to be measured and addressed in a nature-positive manner. The harpy eagle (*Harpia harpyja*) in Amazonian forests illustrates this point.

The harpy eagle is a large apex carnivore of the tropical forest that preys on large arboreal mammals and nests on emergent trees. At the species level, we can assess its presence or absence and estimate whether its population is large enough for viability (minimum 500 breeding individuals). However, this alone is insufficient. As a top-down regulator, the eagle's presence and function are vital for maintaining forest health. It must be widely distributed across the forest to regulate herbivore populations and contribute to ecosystem stability (165). Therefore, both presence and ecological function must be measured, along with human-induced mortality rates (166).

Even if the eagle population appears viable based on individual counts, it cannot persist if its forest habitat or prey species are lost. For example, a 50% loss of forest habitat leads to reproductive failure (167). Moreover, the removal of tall canopy trees, essential for nesting, also reduces population viability, even if forest cover remains above 50% (168). But measuring ecosystem extent alone via remote sensing is insufficient; a species-level assessment is needed to determine whether harpy eagles and their prey are actually present.

Further, if we focus only on species and ecosystem assessments, we overlook key dimensions of natural processes. The Amazon rainforest spans multiple ecosystem types, and its hydrological processes are vital for forest survival. Two forest types, *várzea* and *igapó*, are floodplain forests covering 750,000 sq km and rely on seasonal flooding. Changes to hydrology caused by river channeling, damming, and water diversion threaten their structure, composition, and function (169). Heavily used by harpies, these ecosystems depend not only on local fluvial processes but also on hydrological connections upstream, as far as the Andes (Box 1).

Biome function is also critical to consider for harpy eagle survival. Moisture influx from the Atlantic Ocean initiates rainfall in the eastern Amazon, but forest evapotranspiration generates a significant portion of inland precipitation from there all the way to the Andean mountains (56). The forest recycled water is critical for maintaining upland forests, wet peatlands, as well as rivers and floodplains (170), which in turn support the rainforest ecosystem and frugivorous freshwater fish essential for forest regeneration. If more than 20% of the forest cover is lost, the rainforest could transition into a savannah-like state (57), resulting in the extinction of species like the harpy eagle and the collapse of many "tele-connected" ecosystems (171). This would not only devastate biodiversity but also disrupt agriculture, as the Amazon contributes to precipitation patterns across the Western Hemisphere, and would release vast amounts of carbon into the atmosphere (Box 2).

Hydrological processes

The GBF does not address hydrology. This is a major omission because freshwater regimes, unimpeded riverine connectivity, and unpolluted water are of such significance that maintaining or restoring hydrological processes, water quality, and associated floodplain and delta habitats is the most important NP action for a disproportionately wide variety of terrestrial, freshwater, and marine organisms (137, 172, 173).

Healthy running water ecosystems depend on the condition of their terrestrial watersheds (113) and vice versa. Big river systems, such as the Mississippi in the United States or the Brahmaputra, Tsangpo, Yarlung Zangbo, Jamuna, and Ganges system in South Asia, traverse substantially different biomes, making ecosystem-scale metrics inadequate for monitoring continental-scale structure or function. Rivers and streams embody the key elements of ecological connectivity, providing both unimpeded movement of species and flow of natural processes (174–176). Hydrologic connectivity at the ecosystem scale is particularly important to freshwater vertebrates, whose populations have declined by an average of 83% (177). Large-scale connectivity is also critical for a wide range of terrestrial and avian species that interact with river floodplains (178), and it directly influences water quality (179), sediment flows (180), and fish migrations (181).

Intact hydrological regimes are also essential to maintaining the vast carbon storage capacity of peatlands (42) and mangroves (46, 49) and retaining methane (37). However, river systems throughout the world have been significantly modified by dam construction (49, 182). Ostensibly built to supply low-carbon "green energy", high-head hydroelectric dams are highly nature negative (Box 1).

Freshwater hydrological processes are not limited to water in rivers, lakes, and groundwater (blue water) but also include soil moisture (green water) (183). An essential part of the water cycle, soil moisture transforms into evapotranspiration (vapor flows) in all photosynthesizing terrestrial ecosystems. Green water stocks consist of the soil moisture that feeds all biomass growth. Green water flows are the total flux of vapor, including evaporation and transpiration, as well as interception. Accounting for 60–65% of annual global hydrological flows, they are key to ecosystem functioning and services, supporting food production, biomass on land, and carbon sequestration.

The function of intact forests in green water flows and the climate system is particularly important (121). Stomata (pores in leaves) regulate both water vapor and carbon dioxide (CO_2) exchange between a tree's intercellular space and the atmosphere (184, 185), affecting both precipitation and carbon sequestration. Forests everywhere have a local cooling effect that is lost whenever they are removed (186). Tropical forests and mid-latitude forests to about 40° North also cool the global climate through evapotranspiration. Climate change also causes variations in green water outside normal seasonal cycles, which in turn leads to major reductions in the land carbon sink. (187).

Water vapor from forests is important to rain generation (188, 189). Extensive forest loss can disrupt precipitation patterns across continents (65, 113), heightening the risk of large-scale food insecurity and financial losses (64), especially in the tropics. Tropical forest losses are caused by forest clearing for commercial and subsistence agriculture, logging, charcoal production, and livestock grazing and by uncontrolled fire (190), dams, mining, overhunting (191), roads, and other linear clearings (67). Elimination of seed dispersers due to habitat loss and overhunting impairs forest regeneration (192) and causes declines in carbon storage (193). Deforestation (responsible for 75% of rainfall reduction) and global warming (25% of the reduction) have combined to reduce precipitation in the Amazon Basin by 16 mm per dry season while in areas with heavy deforestation (>28.5% cleared) the rainfall reduction is three times greater due to the added localized increase in temperature and drying (194).

At the global level, assessments of green water reveal dramatic, detrimental changes to the Earth's water cycle (113), resulting in critically important structural and functional losses of species, ecosystems, and natural processes.

Hydrological actions and metrics

There are four dimensions of hydrologic connectivity to be addressed and measured for NP (12, 195):

i) Longitudinal connectivity: connectivity between upstream and downstream (river continuum concept) (196)
ii) Lateral connectivity: connectivity between channel, floodplain, and riparian areas (flood pulse concept) (197)
iii) Vertical connectivity: connectivity between groundwater and surface water (function of hyporheic zone) (198)
iv) Temporal connectivity: hydrogeomorphic change through short and long time periods (shifting habitat mosaic concept) (199).

Actions to halt and reverse the loss of connectivity in the world's rivers align well with the 3Cs:

- C1 (heavily modified landscapes): All four dimensions are likely to be impacted, and restoration is NP.
- C2 (shared landscapes): Retaining existing and repairing impaired longitudinal, lateral, and seasonal connectivity is essential.
- C3 (intact landscapes): Keeping rivers wild and free-flowing is key (200).

An Earth system boundary metric suitable for NP has been developed for natural flows (201), with specific objectives for each of the 3Cs:

- C1: Retain and restore natural flows across landscapes and adjacent marine areas, reduce storm flash flows, and maximize green water retention to mitigate flood risk.
- C2: Aim for a minimum of 80% natural flow retention and restoration.
- C3: Preserve all natural flows in an unimpaired state.

Guidance on maintaining and measuring sediment flows is already available (202). Importantly, while continuing and restoring sediment transport is vital for healthy freshwater and estuarine systems (203, 204), human-induced sediment flux into freshwater systems can be harmful, especially outside normal cyclical seasonal flushes (205, 206).

A global green water planetary boundary metric indicates that no more than 10% of Earth's land area should deviate (in dry or wet direction) from its natural green water variability during the late Holocene (3, 113, 185). Today, 18% of Earth's terrestrial land area exceeds this boundary (3). We discuss this further under the sections *Biome function* and *Biome intactness actions and metrics.*

Biome function

A biome is a large-scale aggregation of related ecosystems (207) characterized by areas of vegetation of the same life form (208), and it is the largest biotic unit after the biosphere. Biome function, tied to intactness, affects continental- to global-scale processes. Despite the absence of biome-specific targets in the GBF, they are needed to achieve both the NP global goal and the GBF's vision.

Biome condition affects rainfall, with widespread effects on carbon storage, ecosystem health, and agricultural productivity, as discussed above and illustrated by Amazon and Congo Basin rainforests (Box 2). Maintaining and restoring forest cover at the biome scale is therefore a priority NP action. Forests are not the only areas where land-use changes affect precipitation. In Western Australia, the clearance of 13 million hectares of dry bush for agriculture using non-native species has directly reduced cloud cover and rainfall relative to areas with native vegetation (209).

The GBF lacks explicit targets or indicators for biome intactness, which should be an explicit conservation objective (210). Indirectly, T1 calls for land-use planning to stop the loss of areas of high biodiversity importance (including ecosystems of high ecological integrity) by 2030. However, action by 2030 is not sufficient. Some tropical forests are on the path toward a tipping point beyond which they may transition into savannah-like vegetation (Box 2). Given recent rates of tropical forest logging, 2030 is too late. Halting tropical forest cover loss and degradation everywhere must be an immediate top priority if these efforts are to protect these biomes, sustain their species and ecosystems, and ensure rainfall throughout the tropics and downwind agricultural regions.

Biome intactness actions and metrics

The best available metric for sustaining rainfall production in tropical forests is to maintain biome-scale forest cover, limiting losses to ≤20% of original primary forest extent (57) and ideally restoring losses to achieve 90% cover to increase resilience to climate change (211). However, some researchers are unwilling to identify any threshold of acceptable forest cover loss (194). For restoration, fast-growing species (including non-natives) aid initial rainforest recovery; the long-term NP goal is to use native slow-growing hardwood species (136, 212). More research is needed to establish a metric for dryland vegetation change.

Migrations

Migration is a specific kind of animal movement where species move between different habitat regions at different times of the year, usually driven by season (213). It has become an urgent conservation problem because not only are migratory populations in decline, but 58% of sites monitored by the CMS are under unsustainable pressure, and 399 endangered migratory species are not even listed for CMS protection (10). In North America, 419 native migratory bird species have experienced a net loss of 2.5 billion individuals since 1970 (214). These losses occur extensively in C1 areas caused by free-ranging domestic cats (mostly unowned) preying on migratory birds (215) and by migratory birds striking illuminated buildings at night (216).

Migration affects species health and diversity (217), ecosystem function and structure (9), and carbon storage in ecosystems (134). Migratory movements range from short seasonal shifts between small habitat patches to transcontinental intergenerational migrations, as seen in monarch butterflies (217). Therefore, conservation strategies focused solely on resident species are insufficient to protect migratory populations (9). Migration is also different from animal movements within a home range to establish a new home range or to find mates in a metapopulation. These all require connectivity but are not migrations (213). Similarly, the need for species to move their range in response to climate change requires connectivity (218), but is not migration *per se* (219), although climate change could lead to migratory range shifts (220).

Migration is not mentioned in the GBF except by implication through ecological and landscape connectivity, which are to be addressed at the country level (GBF T2 and T3) (175). While protecting ecological connectivity across a species' migratory range is essential for migration (10), species movements often transcend national boundaries. The lack of attention to migration is a material deficiency in the GBF because it applies to the CMS as well as to many countries that are not signatories to the CMS.

Migration actions and metrics

For many migrating species, there are well-established approaches to protecting habitats essential for critical life-history events, including wintering and stopover resting habitats, as well as breeding areas (10, 221). These conservation actions require species-specific assessments for NP actions to ensure that habitat patches and their connectivity enable safe breeding, rearing, and travel across a species' full migratory range (222). For sea turtles, for example, a structured conservation framework has been developed to secure their movements across terrestrial, nearshore, and high-seas environments, which could be adapted for other migratory marine animals (223).

Major losses of migratory birds through cat depredation could be substantially reduced by controlling cats in C1 areas (224), and mortality due to building strikes could be greatly reduced by turning off unnecessary lights at night (225). Regarding terrestrial connectivity, metrics to guide conservation efforts are available as outlined by Keeley et al. (226), while conserving hydrologic connectivity is of utmost importance due to its critical role in supporting both freshwater and terrestrial migratory species.

Ecosystem level

The CBD defines ecosystems as a dynamic complex of biotic (plant, animal, and microorganism) communities interacting with their abiotic environment (geophysical, climatic, and chemical processes) (227). Four elements define an ecosystem type: (1) characteristic native species, (2) abiotic environment, (3) key ecological processes and interactions, and (4) spatial distribution (228). While many mechanisms influencing species' vulnerability also apply at the ecosystem level, ecosystems embody natural processes that are not adequately captured through species-by-species conservation efforts (228). This underscores the importance of ecosystem-level actions in biodiversity conservation.

The ecosystem equivalent to species extinction is ecosystem collapse, which occurs when an ecosystem's inherent resilience is overwhelmed, resulting in a phase shift to a different and often novel ecosystem state (229, 230). An ecosystem collapses when one or more key defining variables are functionally impaired, including geomorphological features, species composition, nutrient cycling, disturbance regimes, ecological connectivity, and other biotic and abiotic processes. Vulnerability thresholds have been identified: ecosystems are considered at risk when 30% of their structure is degraded, functionally impaired at 50% degradation, and approaching collapse at 80% degradation (228).

Recently, there has been a discussion of the potential conservation value of novel ecosystems (231). New species assemblages, some of which may be exotic, could create new self-organizing ecosystems that have value for biodiversity conservation or ecosystem function. These emerging systems may warrant conservation attention, but a great deal of research remains to be done on them (232). The primary focus of NP conservation is retaining and restoring the composition and function of native ecosystems.

Some vertebrate species perform processes disproportionately vital to ecosystem function. These species act as ecosystem engineers or keystone species, regulating trophic cascades (e.g., wolves and sea otters), shaping vegetation structure (e.g., elephants and bison), or influencing hydrology and wetland formation (e.g., beavers) (166). Foundational species in nearshore marine environments (e.g., kelp and corals) play critical roles in preserving ecosystem structure (23). Fortunately, small and abundant species that are also vital to ecosystem function benefit from conservation actions that are aimed at suites of larger species through an "umbrella" effect (233), but attention should be paid to their demographic robustness as well (234). Conversely, invasive species can degrade ecosystems by displacing native species and disrupting natural processes.

Ecosystem actions and metrics

NP ecosystem goals will vary according to the 3Cs. C1 areas contain ecosystems that have already collapsed and can be described as crisis ecoregions (235). These landscapes support most of the human population and produce most of the world's food calories, so other important values are at play (143). While ecosystem restoration to full function is impractical under C1 conditions, all remaining fragments of primary ecosystems should be secured, and at least 20% native vegetation cover should be restored to support ecosystem services (236). This includes urban re-greening for multiple ecological and human benefits (237, 238), which is well covered in GBF T12. Agricultural chemicals are most common in C1 areas, which require practices that keep excess runoff out of waterbodies. Safeguarding areas of high agricultural productivity through prevention of urban sprawl serves as an indirect NP practice, preventing further degradation of C2 lands for marginal agriculture and contributing to the SDGs. Combined with improved agricultural practices, dietary adjustments, reduction of food waste, and better global fisheries management, the current cultivated land could feed a global population of up to 10 billion people (239, 240). Such a food systems shift can be done in a just, equitable, and NP manner that halts the loss of intact areas and includes restoration of marginally producing areas to forest cover (241).

NP actions in ecosystems that are less than 50% impaired (C2 areas) should prioritize retaining or restoring overall ecosystem integrity to well above 50%. This requires halting habitat degradation and fragmentation, preserving all remaining intact areas, and retaining and restoring natural abiotic processes, such as fire regimes and hydrology (242). GBF Target 3, which mandates interconnected conservation of at least 30% of land, sea, and freshwater, is particularly well-suited to C2 areas, and such networks will also support climate adaptation efforts (218). Large intact ecosystems (C3 areas) are often aggregated in biomes and should be maintained intact, which requires accelerated action under GBF Target 1.

Across the 3Cs, actions to protect and restore keystone, top-down regulating, and foundational species contribute to NP at the ecosystem level (166, 243). These species also provide positive feedback to the climate system by preventing carbon release and enhancing carbon sequestration (96, 134). Large carnivore and large grazer restoration efforts are best suited to C2 and C3 landscapes. Removals of invasive species can have positive effects across ecosystems (150) and improve green and blue water availability (244). Removing exotic species constitutes an NP action unless they have become part of a novel ecosystem that supports endangered species (245, 246); such exceptions will typically be restricted to C1 areas. Ecosystems also benefit from reducing populations of native generalist species that have become overabundant owing to their adaptability to human-dominated landscapes, the absence of predators, or confined ranges (247), which also aids in zoonotic disease prevention (28).

Species level

Native species are integral to the Earth system, and healthy populations with reliable access to food supplies are less likely to shed pathogens that cause disease in humans (33). The NP goal for species is to increase their distribution, abundance, functionality, and resilience, maintaining genetic diversity and preventing extinctions (91). In contrast, the GBF target for species only focuses on the latter two (T4) (248).

Worldwide, species are in decline due to habitat loss (the primary driver of species loss on land) and overharvesting (the primary driver of loss in the ocean). Other important drivers include industrial production processes, such as deforestation, mining, chemical pollution, cereal crops, and palm oil plantations, the expansion of marginal agriculture, deliberate and inadvertent introduction of invasive species (249), as well as global warming, which alters thermal conditions for species and habitat niches in ecosystems (250).

Species status varies significantly across the 3Cs. At-risk species exist in all three (251), but most are found in C1 areas (143). Moreover, species loss for C1 exceeds detectable presence as many large-bodied species have already been lost from these heavily transformed landscapes (86, 252, 253). In contrast, some largely intact C2 landscapes show remarkably complete faunal assemblages with robust genetic diversity still performing natural processes, such as migration (e.g., Serengeti-Mara). However, while C2 areas often have complete or near-to-complete faunal assemblages, they also suffer from species at risk, extirpations of some populations, declines within populations, and reduced genetic diversity (e.g., large mammals tend to decline first) (86). In addition, their aquatic integrity is often compromised by river damming. C3 areas, being the least disturbed, have few at-risk species, with the primary threat being overexploitation or climate change impacts. However, their sheer size, intactness, and inherent connectivity make them the most resilient of the 3Cs to climate change and least vulnerable to overexploitation (254).

Species actions and metrics

The NP goal to increase the distribution, abundance, function, diversity, and resilience of native species requires halting loss by maintaining intact species assemblages, increasing populations toward ecological functionality, and reducing extinction risk across the 3Cs (Figure 4).

This includes addressing overexploitation of species through enforced regulations or long-standing customary practices, preventing hyper-abundance of species that degrade ecosystems, implementing anti-poaching programs, and promoting active human–wildlife coexistence efforts everywhere.

Maintaining intact species assemblages

Healthy ecosystems that retain the full array of native species interacting with intact natural processes are of the greatest value to the Earth system. They also serve as a barrier against the spillover of potential pandemic-causing pathogens into human populations (131). Despite advances in ecological restoration and species recovery, there is no substitute for preserving original, intact systems. The NP goal of halting nature loss prioritizes the protection of all remaining intact ecosystems and species assemblages wherever they occur—whether in C3 areas, intact parts of C2 landscapes, or in remnant patches within C1 regions. While GBF T4 is silent on maintaining intact species assemblages and abundance, Targets 1 and 3 (spatial conservation) and Target 9 (preventing overexploitation) are aligned with this NP objective.

Restoring functional species populations

Achieving the NP goal of reversing nature loss by 2030 and fully recovering nature by 2050 requires thriving populations. Moreover, NP requires a focus on ecological processes, not just patterns of persistence. The common threshold of an effective population size of at least 500 (Indicator 4 for GBF T4) indicates reduced extinction risk but tells us nothing about whether the species is abundant enough to perform ecological processes at a scale that contributes to Earth system stability (9, 255). Similarly, counting species diversity as a metric of success is insufficient. High diversity of small-bodied species does not compensate for the loss of large vertebrates that perform keystone and regulatory functions such as predation, herbivory, and seed dispersal (243, 255).

The International Union for Conservation of Nature (IUCN) Green Status Framework (163) provides guidance for three NP metrics designed to ensure that species populations are large enough to sustain ecological function across landscapes and maintain resilience:

- Green Status 1 (GS1): The species exists in multiple interconnected populations, each with at least 500 individuals.
- Green Status 2 (GS2): The species is fulfilling its ecological role, with missing species reintroduced where feasible.
- Green Status 3 (GS3): The species exists in a representative set of ecosystems and communities throughout its historical range.

Progressively moving species along this Green Status continuum, from GS1 toward GS3, and maintaining them in a higher status is a contribution to NP (Figure 4). Some C2 systems are close to hosting intact large vertebrate assemblages, often missing only one to three species in the less impacted C2 regions. In such cases, reintroduction is relatively simple and could help move these ecosystems toward GS3 (256). Where species already exist in GS3 status (in many C3 areas), maintaining this state is essential to achieving the NP goal of halting biodiversity loss.

Reducing extinction risk (threatened species)

Preventing extinction is an urgent conservation priority, as the natural background species extinction rate has been greatly exceeded in the Anthropocene (257). Recovery of an extinct species is not yet possible and may never be. Conservation goals should therefore focus on reducing the extinction rate attributable to human activity, which exceeds the natural background rate (258). GBF T4 calls for halting human-induced extinctions of known threatened species and for their recovery and conservation, significantly reducing extinction risk. A key indicator for T4 is the widely used minimum viable population threshold of 500 individuals.

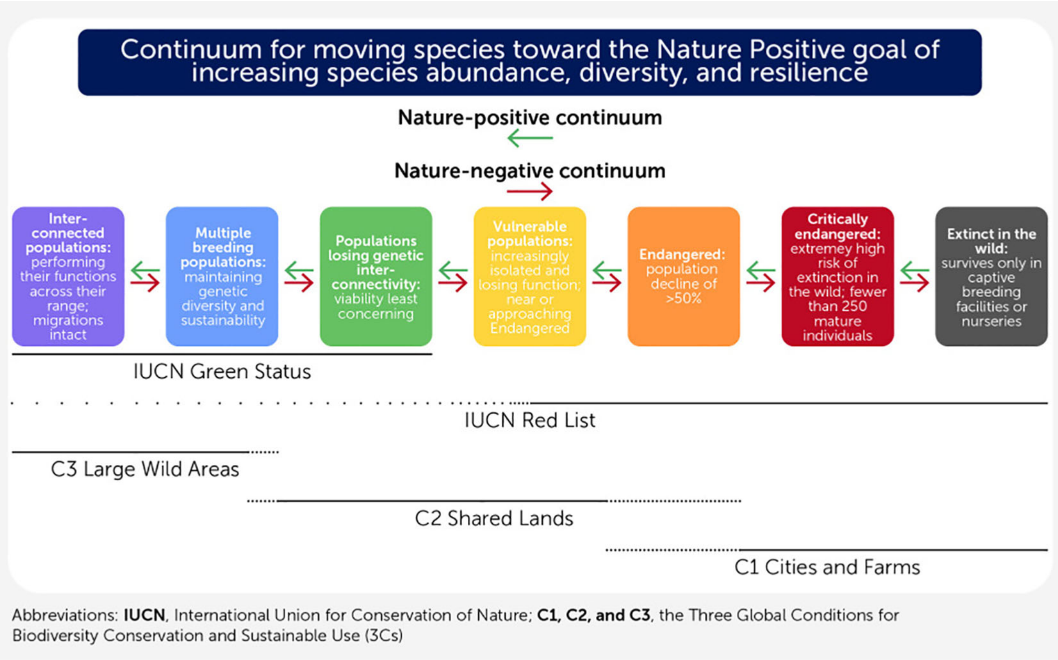

FIGURE 4
Continuum for moving species toward the "Nature Positive" (NP) goal of increasing distribution, abundance, function, diversity, and resilience of species and avoiding extinction. The present trend is either nature negative (i.e., moving species toward the right side of the continuum) or neutral (i.e., static on the continuum). Species on the far left-hand side are already contributing to NP, and their distribution, abundance, and function should be retained to halt biodiversity loss. Actions to reverse species loss and increase their distribution, abundance, function, diversity, and resilience will progressively move species toward the left. At the bottom, the likely location in the Three Global Conditions Framework (3Cs) of species relative to their status along this continuum is indicated. Controlling species exploitation levels is essential across all 3Cs.

The IUCN Red List remains the most comprehensive assessment tool for identifying and categorizing threatened species along a continuum from least concern to global extinction (161). NP-aligned actions for threatened species aim to progressively improve their status along this continuum. Moving each species up one category or more, in a ratchet-like manner, contributes to NP (Figure 4). A "Reverse the Red" campaign actively promotes this approach, emphasizing targeted conservation actions to improve a species' status (259).

A tool for measuring the progress of species toward nature positivity along the extinction risk continuum is the IUCN's Species Threat Abatement and Restoration (STAR) metric (162). Unlike the IUCN Green Status, which focuses on the functional distribution across a species' range, STAR emphasizes reducing extinction risk at specific sites and highlights opportunities for interventions to reduce extinction risk where they are greatest. The STAR system is particularly useful in C1 areas and in the more fragmented parts of C2. For an actor seeking to contribute to NP at the species level, STAR provides a multi-step assessment process that leads to an appropriate threat reduction strategy. The IUCN has published guidance on using the STAR metric to contribute to NP outcomes (260).

Protecting areas to avoid imminent extinction of rare, narrow-range, endemic, and threatened species is an important action under GBF T3, particularly in C1 areas. The Conservation Imperatives approach provides a guide for identifying such priority sites across all 3Cs (160).

Genetic diversity

Genetic diversity is essential for maintaining healthy populations of any size. It is inherently supported by many of the above actions. However, care must be taken to ensure that large populations of recovered species are genetically robust enough to retain resilience, which may require reintroducing genetic diversity (261).

Enabling social and economic conditions for a Nature Positive shift

We now move from conservation actions and metrics to enabling social and economic conditions necessary to achieve the NP global goal. We begin with diverse cultural perspectives, governance, and equity between the Global North and Global South.

Engaging diverse cultural perspectives in Nature Positive

Arising from contemporary empirical science, the NP approach incorporates a holistic understanding of life and a responsibility to act for the health of the planet. It positions human development as being embedded in nature rather than as a competing interest with it (Figure 1) and emphasizes the importance of considering the flow of natural processes over time at varying scales. But not all cultures are driven by empirical science.

Humans interacted with nature throughout the Holocene (262). Many ethnocultural traditions from South Asia, China, Africa, and Indigenous peoples worldwide converge in viewing humans as embedded ecological participants with relational responsibilities to live in balance and harmony with a dynamic natural world, rather than as having rights to exploit static natural resources (263–265). The NP approach is aligned with those cultural perspectives that provide a basis for a shared vision for humanity to live well while respecting nature's biological patterns and natural processes, as discussed further in *Nature Positive Society*, a companion paper to this article (266). Engagement on an equal footing with other cultures' relational and intrinsic values (267) will increase support for NP goals.

Other knowledge systems could also give rise to NP conservation approaches and metrics complementary to those we have outlined. For example, Indigenous and local communities often possess deep knowledge of the sustainability of their ecological contexts based on long-term observation and interactions. This can be embraced alongside empirical science through mutual respectful engagement in "ethical space", where the goal is reconciliation of knowledge systems to achieve NP (268).

Nature Positive governance reform

Meeting biodiversity, climate, and social goals contemporaneously will require greater integration of governance to carefully identify co-benefits, trade-offs, and co-detriments (149, 269) and is urgently necessary to avoid tipping points (270). Yet we lack strong global governance for sustainability. The CBD and UNFCCC/Paris Agreement are structured to place primary responsibility for implementation on state parties, although an International Court of Justice (271) advisory opinion has created the possibility for Global South countries that suffer adverse effects of climate change to sue for damages where a Global North country's failure to meet its commitments has led to direct harm.

In many countries, nature is usually the purview of an environment department rather than fully integrated into high-level decision-making processes, which is necessary if we are to meet global goals (92). Through systemic national-level integration, Costa Rica successfully halted and reversed biodiversity loss from 1990 levels (272). It is common in federal systems for provinces to control land use and, in some countries, for municipalities to govern large areas. Integration of national and sub-national governance, policies, and actions is essential and will be the focus of a global Nature Positive Summit in Japan (273).

Indigenous peoples' territories often have significant biodiversity, but frequently they have been marginalized from governance of those areas, contrary to the UN Declaration of the Rights of Indigenous Peoples (274). Power imbalances and lack of capacity can be addressed effectively and equitably (269) in a bio-cultural approach (275) that moves beyond consultation or financial compensation into design, governance, and financial participation (276). NP governance innovations that embed nature in all aspects of decision-making have emerged from Indigenous peoples themselves—e.g., the Buffalo Treaty among First Nations and Tribes of North America (277) and Māori people initiating personhood for rivers in New Zealand/Aotearoa (278).

Nature Positive shift and finance

Funding is required to implement conservation measures. Informed by the Paulson Report (279), GBF T19's funding target to implement national biodiversity strategies and action plans is at least US$200 billion from all sources. This includes overseas development assistance (ODA) from rich nations of at least US $20 billion annually by 2025 and US$30 billion annually by 2030, which we discuss next in the context of equitable sharing of responsibilities between the Global North and Global South.

Equitable sharing of responsibilities between the Global North and South

In the developed North, advanced economies must conserve remaining intact nature, restore degraded natural systems, and decarbonize at their own expense. This transition requires strong political will, which could be driven by self-interest: continued environmental degradation will destabilize economies (80), threaten capital stocks (83), and intensify political instability through increased climate-related displacement and refugee crises (280).

In the Global South, similar actions are required. While degradation of nature occurs in both wealthy and poorer nations, the consumptive footprints of the Global North and newly industrialized nations are major drivers of biodiversity loss in developing regions. Similarly, climate change—primarily caused by emissions from wealthy industrialized countries and, more recently, by rapidly developing economies (281) —disproportionately affects poorer nations (282). Financial transfers from developed to developing nations are therefore equitable (283–286).

Both the CBD and UNFCCC have agreed on financial commitments. GBF Target 19 calls for overseas development assistance from rich nations of at least US$20 billion annually by 2025 and US$30 billion annually by 2030. A multilateral mechanism for the fair and equitable sharing of benefits from the use of digital sequence information on genetic resources, including a global fund, has also been agreed (99). The UNFCCC has an agreed US$300 billion annual resource mobilization goal from North to South by 2035. It also operationalized a Loss and Damage Fund, with US$730 million in initial pledges (287). Fulfilling these commitments is critical for achieving shared environmental goals equitably.

Many Global South countries struggle with national debt burdens, which restrict the financial resources available to them for both human development and NP implementation. Debt for nature swaps (DNS) started as an international public finance incentive to protect nature, involving debt forgiveness in exchange for conservation commitments (288). More recently, DNS have involved a reduction in the cost of borrowing for a developing country in return for NP actions (289, 290). Concessional finance from multilateral development banks (MDBs) or guarantees from rich countries improve the investment grade of developing countries' debt, which reduces interest rates. Such debt cost reduction projects have been implemented in several countries with NP conservation outcomes (291, 292).

Nature Positive transformation of the dominant economic system

The NP shift also requires a transformation of the dominant economic system, which is recognized in the GBF. We discuss how this can be enabled by valuing nature in public accounting standards, and through ODA, MDBs, innovations in financial markets, and changes in business operations. We begin with valuing nature.

Valuing nature

T14 calls for changes in national accounting and fully integrating the values of biodiversity. Many people attach non-economic value to nature (293, 294), but the world's dominant economic system does not. There are critiques of attaching financial value to nature because it undervalues or ignores values reflective of human–nature relationships (267) and could result in privatization of public goods (295) or economic imperialism (296). However, achieving the NP shift will require alignment of the dominant financial system, which is currently driving the loss of biodiversity (80, 297). We focus first on public sector mechanisms to attach economic value to nature in national accounts.

Public sector finance and Nature Positive

The global financial system treats "natural assets" as free for the taking with the only cost being the expense of extraction or harvesting (80). The result is private enterprise capturing the value at the expense of the common biosphere (298). Private enrichment with externalized costs is counted as a positive number in standard national accounts and Gross Domestic Product (GDP) (299). Thus, nature-negative actions are counted as positive economic outputs in government finances. For the world to become NP, governments must address this systemic problem through standards, regulations, and the creation of market mechanisms (80).

The externalized cost of economic activity can be viewed as depreciating the "natural capital" that underpins the economy and human well-being, but without accounting for that loss of value to society (80) (Figure 1). Valuing natural capital and ecosystem services is an effective way to correct this by measuring and counting the value to society alongside the extracted value realized by an individual or corporation (80, 300). Natural capital (also known as tangible natural assets or stocks of nature) produces flows of ecosystem services that can be measured through a "shadow" price. In 2012, the UN System of Environmental-Economic Accounting (SEEA) created a statistical Central Framework (CF) that enables countries to measure their natural capital and understand the contributions of nature to national prosperity and the importance of protecting it. Building on the CF, the UN also developed SEEA Ecosystem Accounting (SEEA EA), which provides a more in-depth view of the health of natural capital in each jurisdiction (301, 302). So far, over 90 countries compile accounts using SEEA CF, while over 50 countries also use the more detailed SEEA EA. However, these statistical frameworks are satellite standards to the System of National Accounts (SNA) and therefore have limited influence on how GDP is calculated by countries. To make an NP change, governments must meaningfully integrate SEEA EA into their system of national accounts and use this information to inform public sector decision-making.

Another avenue for integrating the value of natural capital into mainstream financial markets is to address barriers that limit the value of nature from being accounted for in public sector accounting standards. Currently, intact nature is left out of international accounting frameworks, and its economic value is not counted until it is exploited, purchased, or sold. Even formal area-based conservation actions by the state are viewed as an expense rather than an investment, and the resulting conservation areas are not viewed as assets in public accounting. However, in January 2026, the International Public Sector Accounting Standards Board (IPSASB) released IPSAS 51, Tangible Natural Resources Held for Conservation, which will allow governments to count conservation areas as tangible natural assets (303, 304). Getting countries to adopt this new accounting standard will be an important NP action (305).

Private sector investment in conservation

T19 seeks to increase private investment as part of the US$200 billion for conservation measures, but it provides no pathways for it. In market terms, nature is worth more dead than alive. New markets for the "social value" of nature are needed (80), whether through regulatory support or capital market evolution.

Nature markets began with "no net loss" biodiversity harm mitigation laws, such as the United States Clean Water Act (306) and the United Kingdom's biodiversity net gain requirement under the Environment Act 2021 (307). Since these markets are inherently about mitigating loss, they can lead to further degradation of an intact area "offset" through restoration of a degraded area. This can help the world move toward less loss on the road to nature positivity (91, 308), but more than an offsets market is required to engage private investment to halt and reverse nature loss.

The European Union is evaluating a voluntary nature credits system (309). It builds on earlier private and government efforts to create biodiversity credits to sell to the private sector (310). Biodiversity credits require additionality, which means some improvement in the conditions of the underlying nature asset. Additionality is good for reversing loss through restoration (310). The International Advisory Panel on Biodiversity Credits (IAPBC) also includes improved governance and protection as an additionality. This may include Indigenous stewardship agreements or legal designations that did not previously exist (310). Biodiversity credits are of interest to buyers motivated by charitable or social license considerations but not to investors who seek a financial return on investment.

Unlocking large amounts of private capital for intact nature will require financial innovations (311) that provide a return on investment or reduce risk to capital. Governments can stimulate the creation of market mechanisms through concessional finance. This approach underpins the innovative Tropical Forest Forever Facility (TFFF), intended to attract private investment to halt the loss of tropical forests. Led by Brazil, TFFF was launched at UNFCCC COP30 in Belem. Its goal is to raise an initial US$25 billion from MDBs, ODA, and philanthropies to invest and also improve the investment grade of US$100 billion of debt to be sold to private investors. The resulting US$125 billion fund would then be invested to generate returns above the cost of borrowing, which is expected to net US$4 billion a year. This would be paid to governments of tropical forest countries to halt deforestation, with a specific percentage of the funds earmarked for Indigenous and local communities (312). In the month it was launched, there were over US$6 billion in pledges toward the initial US$25 billion (313).

Heightened awareness of nature risk and interest in investing to reduce it (314) could create a market for halting the loss of nature. Large investors are "universal owners" of climate and nature risks because they are widely invested in the global economy (315). Thus, ensuring the stability of the Earth system represented by natural capital is in their business interest, and they could invest in it. There is an existing natural capital protocol for business (316, 317) that is consistent with SEEA (318, 319). Initiatives to "put nature on the balance sheet" have identified the limitations in accounting standards and frameworks that prevent the inclusion of non-purchased natural assets in financial statements and provided a road map for addressing the problem (319).

The International Organization for Standardization (ISO) released the world's first international biodiversity standard in October 2025. ISO 17298 "Biodiversity — Considering biodiversity in the strategy and operations of organizations — Requirements and guidelines" provides companies, investors, and public institutions with a globally agreed rulebook for how to measure, manage, and report their relationship with natural capital (320). For the private sector, this defines how biodiversity risk enters credit rating, audit trails, and shareholder expectations.

Meanwhile, natural asset companies create an asset class for nature, enabling direct investment in protected natural capital (321). Similarly, insurance arrangements focused on avoiding loss of natural capital, in which part of the premiums received are invested in nature to reduce the likelihood of loss of ecosystem services vital to a particular economic sector, could be created. To stimulate the market and create a level investment environment, governments could regulate financial institutions and businesses to hold some percentage of their assets as natural capital (this could also create a market for biodiversity credits).

Local and Indigenous communities should be involved in the design, returns, and governance of nature and climate investments that affect their areas to ensure both equitable outcomes and security of title. Including traditional knowledge systems will also likely enhance the performance of the underlying nature asset (269).

Private sector operations and subsidies

The NP shift requires economic transformation beyond government finances and private markets. Economic factors and consumption patterns are major drivers of both biodiversity loss and climate change and must be fundamentally transformed if we are to achieve the NP global goal (322). Here, we focus on realigning business operations.

Business interests have been involved in NP efforts since its inception, including in co-authoring the foundational NP paper (91) and successfully supporting the inclusion of targets in the GBF that encourage businesses to make an NP shift (317). The aims are as follows:

- All sectors should align their activities with the GBF (T14).
- Corporations should reduce their impact on nature and report their dependencies on nature (T15).
- Governments should eliminate US$500 billion in nature-negative subsidies to business by 2030 (T18).
- Corporate and financial sectors should participate in GBF financing (T19, discussed above).

T14 and 15 have attracted significant interest from both operating companies and the financial sector (323), and there was substantial private sector participation at the Global Nature Positive Summit hosted by Australia and the state of New South Wales (324). In 2025, the World Economic Forum reported growing consensus around business alignment with the NP goal (325).

To transform operations, businesses will need to embed NP approaches across all business decisions (317). Alignment methods include both internal decision-making tools (such as the Natural Capital Protocol) and disclosure-related tools. The Task Force on Nature-related Financial Disclosures has developed voluntary guidance (adopted by hundreds of companies and financial institutions) to help businesses integrate nature into decision-making and shift financial flows away from nature-negative outcomes and toward nature-positive outcomes. (326). The Nature Positive Initiative is developing voluntary corporate NP metrics for businesses to make meaningful and reportable contributions to the global NP goal (327). Science Based Targets for Nature is developing a drivers-oriented framework to help companies align their activities with NP (328).

Measures like these will be mandatory in the European Union, which has passed rules scheduled to come into force in 2027 that will require companies to report on "sustainability matters" (environmental, social and human rights, and governance factors), including their supply chains and actions to prevent or mitigate adverse impacts (329).

Many of the world's largest mining companies have collectively endorsed NP, asserting that "nature positive must be both an objective to be achieved, as well as an embedded approach to doing business" (330). Industry-specific NP approaches have now been proposed for the mining sector (331), the agricultural sector

(239), and wind farming (332). The Nature Positive Universities Initiative involves 500 private and public higher education institutions across the world committed to promoting nature on their campuses, in their supply chains, and within their cities and communities (333). There is also a well-developed mitigation hierarchy available for businesses to reduce inevitable impacts as part of the transition to NP (334). Rigorous attention to achieving assured NP outcomes will be required to avoid "greenwashing" (335, 336).

T18 materially understates the flow of public subsidies to private activities that must be changed: there is an annual net US$7 trillion in nature-negative financial flows, US$5 trillion of which are private (337). This requires public policy shifts in incentives (279), which will be more likely to happen with business support.

An NP world will only be achieved if there is a transformed, enabling economic environment. This requires alignment of financial incentives, business operations, innovation to make intact nature investable, public and private investments in conservation, and integration of government actions across the treaties.

Integration through co-reporting progress toward Nature Positive, climate goals, and the Sustainable Development Goals

We have demonstrated that achieving the SDGs and global climate goals is intrinsically linked to the NP goal. An explicit overarching objective for all three should be the integrated pursuit of an equitable, nature-positive, and carbon-neutral world (91).

Now that there is recognition of the nature–climate nexus from the parties to the CBD and UNFCCC and also the International High Court, national governments should align their reporting of Nationally Determined Contributions (NDCs) under the Paris Agreement and National Biodiversity Strategic Action Plans (NBSAPs) under the GBF. At CBD COP16, an initial step toward this integration was made by "urging … parties to consider integrating into their NBSAPS … approaches … to climate change adaptation and mitigation" (99).

NBSAPS could immediately include carbon sequestration and storage indicators under GBF Targets 1–3 and 11. Similarly, the SDGs should explicitly acknowledge the GBF in SDG 14 and 15, as they currently recognize the Paris Agreement in SDG 13. Integrating NBSAPs and NDCs could be facilitated through the existing architecture under provision 4.19 of the Paris Agreement, which calls for long-term low-emission development strategies (338). Joint reporting across the Paris Agreement and CBD/GBF could also serve to track progress on SDGs 13, 14, and 15, while incorporating shifts in production and consumption patterns and the transformation of subsidies, aligning with SDG 12.

Both the GBF and Paris Agreement emphasize equitable outcomes, which are also a focus of SDGs 1–7, 16, and 17. Joint reporting on equity across these global agreements would mark a major advance as it would foster integrated thinking, improve efficient deployment of financial resources, address underlying drivers in a coordinated manner, and achieve positive outcomes for both people and the Earth system. All of this joint reporting across the GBF, UNFCCC/Paris Agreement, and the SDGs should start immediately. As a further step, the integration of planetary boundaries and equitable objectives has been proposed through the concept of safe and just Earth system boundaries (104), for which Rockström et al. (201) provided Earth system boundary metrics. They should be widened to include the species, ecosystems, and natural processes discussed above. These global metrics could then be used by governments to assess progress toward living within all nine planetary boundaries.

Conclusion

The Earth system is rapidly unraveling. Protecting intact nature and restoring damaged ecosystems must be prioritized in global policy to the same extent as climate action under the Paris Agreement and the SDGs for human development. Realizing the GBF's NP mission, goals, and targets, with heightened attention to natural processes and feedbacks, would be an essential stabilizing action. However, actions under the GBF alone are insufficient. We are at or near the critical threshold of 1.5°C of climate warming (339–341), beyond which the Earth system could cross tipping points (59).

Concerted, aligned, and monitored efforts across the CBD, UNFCCC, SDGs, and all of society are needed to create an NP future that is equitable and carbon neutral. To achieve this requires conservation action and an enabling social and economic environment that includes money to pay for it, reorientation of financial flows, a shift in production and consumption practices away from nature-negative activities toward positive outcomes, new financial mechanisms, and stronger coordinated governance that is equitable and people positive.

It is a grim irony that just as the need for integrated action at all scales has become both apparent and urgent, the UN system and multilateralism in general are under enormous pressure (309). Time has shown, however, that what is urgent eventually becomes apparent to even the most reluctant. There remain many actors who are both deeply concerned about the state of the world and highly committed to improving it, including a broadly based Nature Positive Initiative (342).

Achieving the NP goal of halting and reversing nature loss, with a net improvement by 2030 from a 2020 baseline, is essential for the well-being of humanity and the rest of life. It is the only pathway to ensuring that the 21st century progresses toward peace, prosperity, stability, better health, and natural beauty, rather than descending into a future marked by large-scale human displacement, violent conflict, fires, floods, disease, food and freshwater shortages, inhospitable climates, and ecosystem collapse.

It is time for us to recognize that nature is the foundation of all human affairs. Unless we act swiftly to make the world NP by 2030, our lives are likely to become very difficult in a destabilized Anthropocene.

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Author contributions

HL: Writing – original draft, Conceptualization, Writing – review & editing, Visualization.

JR: Writing – original draft, Conceptualization, Writing – review & editing.

RP: Writing – original draft, Writing – review & editing.

DL: Writing – original draft, Writing – review & editing.

LL: Writing – original draft, Writing – review & editing.

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LZ: Writing – review & editing, Writing – original draft, Visualization.

RS: Writing – review & editing.

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Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

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Perspective

Governing for "no net loss" of biodiversity over the long term: challenges and pathways forward

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SUMMARY

Economic development is increasingly impacting biodiversity, leading to a rise in biodiversity offset policies globally that aim to compensate for biodiversity losses. Many developments generating offsets create long-term, irreversible losses of biodiversity and, therefore, require biodiversity gains from offsets to be retained over the long term to have any hope of achieving "no net loss" (NNL) of biodiversity. This raises important ecological and institutional challenges that current offset mechanisms, built for politico-economic systems with short-term policy horizons, do not sufficiently consider. We explore this issue and discuss several responses to the problem ranging from incremental changes for improving on-ground management, through to major governance shifts required to support the long-term social-ecological resilience of offset sites. We argue that without these changes, at best, NNL policies participate in temporarily reducing permanent biodiversity loss. At worst, they participate in a false promise, distracting institutions from the transformative changes needed to reverse biodiversity depletion.

INTRODUCTION

With the increasing environmental impacts of economic development, biodiversity offset policies are spreading globally, aiming to compensate for the biodiversity losses induced by these activities, notably in the infrastructure, urban development, and extractive sectors.[1] Biodiversity offsetting (henceforth referred to as "offsetting") is defined here as a set of institutional rules and practices that enable the production and retention of "biodiversity gains" across time and space to compensate for the loss of biodiversity from authorized damage, with the aim of reaching "no net loss" (NNL) of biodiversity (Box 1, and references therein). Although regulations, policies, and voluntary practices can define offsetting in different ways,[2,3] here we focus on regulatory offsets and follow the terminology commonly used in the academic literature and best practice offset guidelines (Box 1). Offsetting usually corresponds to the last step of the mitigation hierarchy (Box 1) where the first step is to avoid impacts, followed by minimizing and remediating impacts. Finally, offsetting mitigates the remaining residual impacts on biodiversity.

Both biodiversity offset schemes and the NNL objective are already operationalized in multiple jurisdictions around the world.[1,22] This uptake of offsetting schemes has been driven by the search for reformist solutions to conflicts over limits to development occurring across scales, including infrastructure and extractive activities.[3] Offsetting theoretically enables the operationalization of the "polluter-pays" principle (Box 1). This conceptualization takes the current politico-economic system as a given, often proposing solutions based on technocratic approaches that empower the state, markets, and experts.[3]

Despite this global uptake, offsetting and NNL have remained controversial within the field of conservation.[3] For example, the ecological feasibility of recruiting biodiversity gains through ecological restoration and/or by averted losses (Box 1) has been questioned, due to the limits, uncertainties, and inherent time lags associated with both restoration and the accrual of averted losses.[7,11,23,24] In addition, the current institutional capacity to deliver and maintain gains has been questioned due to limited evidence on offset effectiveness.[4,25]

Best practice guidelines for biodiversity offsetting specify that offset gains need to be maintained until the authorized impacts on biodiversity cease, and preferably in perpetuity.[12,15] Thus, the retention of biodiversity gains over the long term is a critical aspect of offsetting as developments generating offsets often create long-term and irreversible loss of biodiversity. The capacity to retain gains over the long term is therefore a fundamental requirement for offset schemes to deliver on the promise of NNL. Yet, this temporal commitment inevitably stumbles due to the fact that Western institutions are structurally blind to long-term concerns,[26,27] being constructed to consider time frames of no more than few decades, and often much shorter periods based on policy cycles.

In this perspective, we investigate key challenges associated with ensuring the recruitment and retention of offset biodiversity gains over long periods of time. Using an interdisciplinary lens that draws from both natural and critical social sciences, we examine these challenges by (1) presenting key relevant concepts underpinning biodiversity offsetting, (2) clarifying the time frames involved in recruiting and retaining offset gains, (3) presenting some of the key approaches currently promoted and/or implemented to recruit and retain biodiversity gains "over the long term," and (4) critically reviewing these approaches and proposing pathways to move forward.

Box 1. Glossary of key concepts used in the offset and social sciences literatures

Additionality: all recruited gains should not have occurred in the absence of the offset project and are fully additional to the expected scenario without the offset.[4]
Anthropocene: a proposed new geological epoch induced by the impacts of human activities on the Earth system since the industrial revolution of the late eighteenth century and accelerating since the 1950s; characterized by changes in major features of the system's structure and functioning, including the climate system, the water and nitrogen cycles, and biosphere degradation.[5,6] These changes are and will cause major shocks to the social-ecological systems that have thrived in the previous epoch, the Holocene.
Averted-loss or avoided-loss offsets: offsets aiming to prevent future biodiversity loss via actions, such as the protection of existing biodiversity that mitigate threatening processes that would otherwise cause the depletion or loss of biodiversity.[7]
Biocultural diversity: "the diversity of life in all of its manifestations—biological, cultural, and linguistic—that are interrelated (and likely coevolved) within a complex socio-ecological adaptive system."[8]
Biodiversity: "the variability among living organisms from all sources, including, inter alia, terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species, and of ecosystems."[9]
Biodiversity surrogate: a representation of biodiversity. Surrogate metrics are often promoted to measure and account for biodiversity losses, recruited gains, and their equivalence.[4,10]
Equivalence: when the measured losses and gains in biodiversity surrogates are the same in nature and magnitude.[11]
Like-for-like or better rule: the recruited gains benefit either the same biodiversity surrogate as impacted by the development, or benefit another surrogate considered of a higher value (e.g., more threatened) than the impacted one.[4,12]
Mitigation hierarchy: the mitigation hierarchy is a series of four steps to be followed during the life cycle of a project impacting biodiversity: avoid, minimize, remediate, and offset residual impacts. It is to be deployed when the options of renouncing to the project or selecting alternatives have been disregarded.[2,12,13]
No net loss (NNL) or net gain: objective of the mitigation hierarchy and its offsetting step. The frame of reference against which NNL is to be evaluated (i.e., the counterfactual) should be specified to avoid unreasonable expectations in the actual achievements of the NNL objective.[2,14]
Offset project: set of offset measures that ensure that residual impacts, if any, are compensated by equivalent gains. Gains are usually accrued after the permit has been granted, unless gains are accrued in anticipation of future losses via "banking."[15]
Polluter-pays principle: principle founded in welfare economics, proposing to internalize negative externalities induced by damaging activities into the market, via monetary compensations (taxes) set at the level of the lost values. The expression "polluter-restores," not commonly used, better reflects the transposition of the principle to biodiversity offsetting, where preferred compensations take the shape of restoration-related activities rather than monetary compensations.[16]
Regulatory offsets: offsets that are deployed for projects with significant impacts on biodiversity-related matters, as part of permit conditions under conservation-related regulations; for examples, see Sundseth and Wegefelt,[17] the Australian Government,[18] and the US EPA.[19]
Resilience: "the capacity to persist in the face of change, to continue to develop with ever changing environments."[20]
Voluntary offsets: offsets that are not prescribed by law and deployed on a case-by-case basis, following a voluntary initiative of a party impacting biodiversity.[21]

KEY CONCEPTS OF OFFSETTING

Best practice suggests that offsets should follow the "like-for-like or better" rule and meet the "additionality" requirement (Box 1). In practice, offsetting uses biodiversity surrogates to measure losses and gains because the full set of components and processes that make up "biodiversity" cannot never be practically measured (Box 1). Different biodiversity surrogates (and their metrics) capture different aspects of biodiversity, ranging from utilitarian valuations to more ecocentric ones that attempt to capture ecological function or the maintenance of individual species.[28] In practice, surrogates used in regulatory offsets are often based on the components of biodiversity protected under conservation-related legislation, and are reflected in simple metrics, such as acres of suitable habitat for threatened species (e.g., US Endangered Species Act and French compensatory practices[29]) or habitat hectares of native vegetation (Planning and Environment Act 1970 in VIC, Australia).[30] The choice of surrogate has strong implications for the implementation of offset schemes; for example, the more ecologically complex a surrogate is, the more difficult it is to find an equivalent (like-for-like) biodiversity offset.[28]

In the offset literature, two phases are commonly differentiated for reaching an NNL, measured through the relevant biodiversity surrogate. In the first phase, gains are recruited through initial on-ground management actions and, in best practice standards, the legal and physical protection of offset sites. Depending on the contextual conservation challenges (e.g., background trends, surrogates being offset, and legal obligations), gains are progressively accrued over time via three different strategies which we label A–C: approach A—the establishment of an ecosystem or ecological community in a location where it did not exist previously, an approach commonly used in wetland mitigation;[31,32] approach B—the ecological restoration of degraded sites to their former ecological composition and function;[11] or approach C—averted (or avoided) loss, the removal of

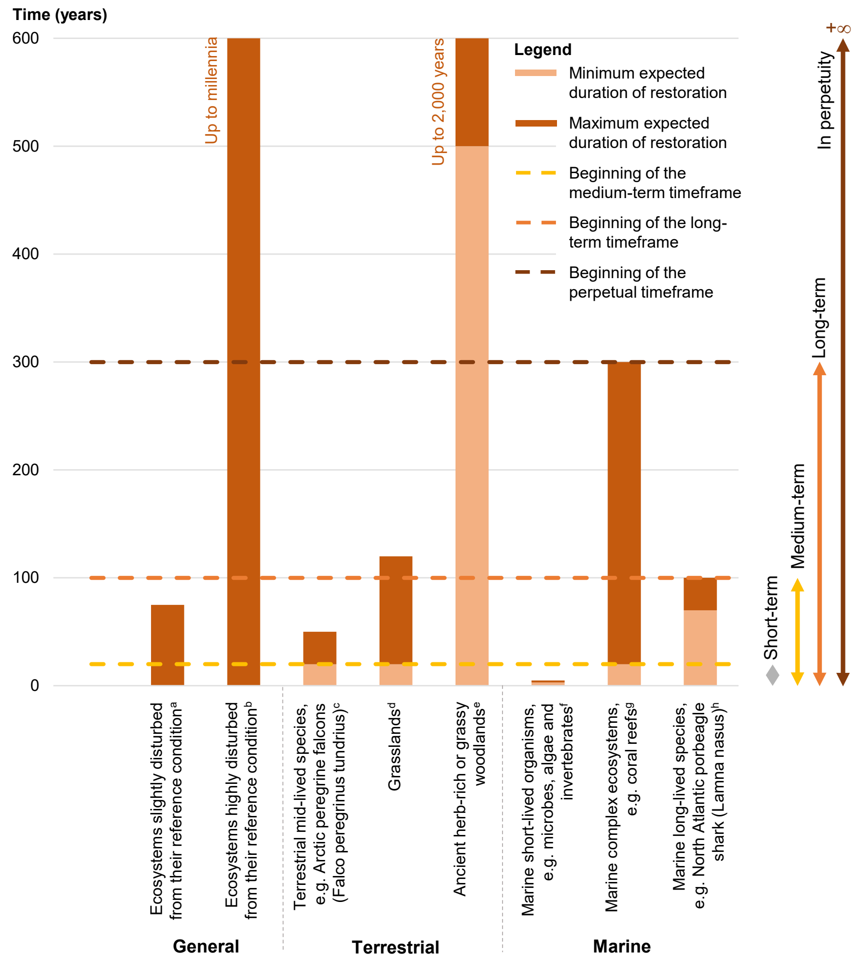

Figure 1. Examples of restoration and recovery time frames for ecosystems and species populations

The indicated time frames are the ones we propose based on the restoration literature (see Tables S1 and S4 for references). Ecosystem restoration and species population recovery and survival depend on the starting system state, reference condition, multiple social-ecological factors that are interconnected, and the influence of stochastic environmental events, including human-induced climate change (see Table S4 for the references). [a]Potential full recovery within a human lifetime, with a global average life expectancy of 75 years; recovery depending upon availability of propagules and appropriate landscape-scale ecological processes. [b]Reach millennia; probably not restorable but will likely form novel ecosystems. [c]Dependent upon, for example, population density, habitat quality, and climate. [d]Dependent upon, for example, nutrient loading, soil structure, and availability of propagules. [e]Dependent on soil chemistry, mycology, and availability of propagules. Restoration a possibility for plant assemblages but questionable for rarer invertebrates and vertebrates. [f]Dependent on amelioration of environmental stressors and availability of biological resources. [g]Dependent on appropriate marine biological conditions and protection from environmental stressors; for example, habitat destruction and coral bleaching. [h]Dependent on the implementation and enforcement of sustainable fishing practices, protection of habitat, and appropriate marine biological conditions.

threatening processes thereby avoiding declines in condition (e.g., averting weed invasion) or complete loss (e.g., avoiding land clearing).[7] Approach B may involve ecological management and/or the (re-)establishment of traditional land-use practices.[33,34] Despite limitations, approaches B and C remain the most common, and some offset policies combine them.[7,35]

The second phase starts once sufficient gains have been recruited. The objective of this phase is to retain accrued biodiversity gains until the impacts of the authorized project cease.[12,15] When moving to the retention phase, it is usually assumed that sufficient gains have accrued as measured by the biodiversity surrogate, and that the associated ecological components have become resilient and self-sustaining, with no (or minimal) human intervention, beside the continuation of traditional land-use practices when relevant.

Target-based offsets have been recently conceptualized as a way to better align project-level offsets with jurisdictional biodiversity targets.[36] This approach involves setting retention targets for given biodiversity features and specifying trajectories—"net gain," NNL, or "managed net loss"—based on the states of biodiversity features relative to their targets. The offset actions (comprising of approaches B and/or C) are then calculated such that, with development and offsetting continuing, retention targets will (theoretically) never be breached due to the amount of protection and/or improvement from offsets.[36] However, once calculated, offsets within this target-based approach still apply the same practices as current offset policies, and thus still face the same challenges regarding the recruitment and retention of biodiversity gains over long periods of time.

In both the gray and academic offset literature, the terms "long term" and "in perpetuity" are commonly used in reference to the duration of the retainment phase, but often without being precisely defined. It is thus critical to clarify the range of time frames implicitly assumed by these terms when applied to offsetting activities; a task to which we now turn.

DEFINING THE TIME FRAMES OF BIODIVERSITY OFFSETTING

Here, we propose definitions for short-, medium- and long-term time frames, based on ecological considerations (Figure 1). Our proposed definitions are based on restoration time frames obtained from a diverse set of biodiversity surrogates described in the restoration literature: short term (<20 years), medium term (20–100 years), and long term (100–300 years); we take in perpetuity to mean more than 300 years or "forever more" (for references, see Figure 1 and Table S1).

Using these restoration time frames (Figure 1), phase 1 (the recruitment phase) can range from a few decades through to beyond a century when recruiting equivalent gains for complex ecosystems and long-lived species. Conservation legislation remains biased toward long-lived vertebrates (especially mammals and birds),[37,38] as well as complex ecosystems and other biodiversity features that are in good condition, rare, and/or threatened.[39,40] Consequently, surrogates generated for like-for-like offsets based on these biodiversity features are likely to require medium- to long-term time frames if recruited through approach B (restoration), and even longer under approach A (establishment of ecosystems). As demonstrated by the restoration literature, there is large variability in the time frames needed for restoration of ecosystems and species (Figure 1, and references therein). These range from slow-growing, high conservation value ecological communities (e.g., old-growth forests and species-rich grasslands), to biodiversity surrogates that can be restored or established over shorter time scales, such as dynamic ecosystems comprising fast-recovering species that can adapt to multiple habitats or thrive in modified habitats (Figure 1). Best practice offset guidelines also encourage the use of complex surrogates that require medium- to long-term recruitment time frames due to the complexity of, for instance, "species composition, habitat structure, and ecosystem function and people's use and cultural values associated with biodiversity."[41] Regarding averted-loss offsets (approach C—the removal of threatening processes), if properly designed,[7] this strategy could potentially accrue gains slowly or rapidly, depending on the likelihood of occurrence of the averted threat and its potential impact.[42,43] However, little research has been done to estimate time frames for accruing gains due to averted-loss; therefore, we have relied solely on the restoration literature to define expected time frames.

These recruitment time frames bring ecological challenges. The recruitment of biodiversity gains for offsets involves working with a range of interconnected biophysical processes and functions, including nuanced species interactions that are variously subject to natural disturbance regimes overlaid with anthropogenic impacts, such as human-induced climate change and landscape transformation.[44–46] In combination with limited ecological restoration and re-establishment knowledge,[47,48] this results in significant uncertainties regarding both what biodiversity has been lost, and therefore what needs to be recruited, and whether recruitment attempts can deliver appropriate and equivalent biodiversity gains that can then be retained.[11,49] These uncertainties imply that biodiversity gains from offsets will often be unlikely to fully compensate for biodiversity losses from development.[11,49,50]

While the time frame of the recruitment phase (phase 1) depends on the biodiversity surrogate being offset and the actions being undertaken, the retention phase (phase 2) is bound by the duration of the impacts on biodiversity that generated the offset. In practice, many authorized impacts that trigger offsets are effectively permanent because of the type, duration, and magnitude of the disturbances they induce on biodiversity. The fact that only significant biodiversity impacts require a permit (and therefore offsets) to be legally authorized[9,17,18,19] means that most impacts requiring offsets are thus by definition "significant" impacts and likely to result in long-term or permanent losses. For these cases, phase 2 (the retention of biodiversity gains) then needs to cover time frames in the order of centuries to meet any practical definition of in perpetuity. This also explains the stated preference for the perpetual protection of offset gains in leading policies and offset standards.[12,51] There have been institutional innovations in Australia and the US in attempting to strengthen the long-term protection of offset gains,[32,52,53] and concerns have been expressed over the long-term protection of offset sites in Europe.[54,55]

LONG-TERM GOVERNANCE IN GUIDELINES AND POLICIES

Here, we briefly review the time horizons specified in leading offset policies and best practice literature, and the range of recommended institutional arrangements mentioned in these sources to recruit and retain biodiversity gains, for the long term or in perpetuity.

Duration of offset obligations

Best practice guidelines and leading offset policies, from the US, Australia, and within Europe, vary in the time frames used for the recruitment and retention phases of biodiversity gains (Table 1). They tend to associate the recruitment phase (phase 1) with a time span of 5–30 years, and the retention phase (phase 2) with a time span of 20–50 years, which is often framed as long term (Table 1). These time frames align with policy cycles and life cycles of major development projects (Figure 2), but only correspond to short- to medium-term ecological time frames (Figure 1). Therefore, they do not match the long-term ecological time frames required to recruit or retain gains for long-lived and complex biological features that trigger biodiversity offsets (Figure 1). Based on our review, there is currently little to no engagement with time horizons expanding beyond 50–100 years within existing offset policies or within the best practice literature. The exception is the reference to the in perpetuity concept in Common law, mainly in the US and Australia, although the efficacy of the mechanisms deployed to achieve this are not well understood and have limitations.[56,57]

In the next subparts, we expand on the existing and proposed mechanisms that the best practice literature has promoted to improve the recruitment and retainment of gains beyond a few decades. These mechanisms are also listed in Table 2, columns 1 and 2.

Legally securing the gains

Three legal instruments have been proposed to protect the biodiversity gains on offset sites from incompatible land uses over time (Table 2, "legally securing the gains"). Without these legal instruments, the offset measures to recruit and retain gains are solely bound to the permit conditions of the development project and associated contractual obligations, and thus, are at risk of lapsing once the project's contract ends. The proposed legal mechanisms rely mainly on offsetting experiences from the US and Australia (Table 2, "legally securing the gains") and include: (1) the transfer of land ownership rights to the state, to transform an offset site into a publicly accessible conservation reserve, preferably associated with a land stewardship agreement that supports appropriate management practices; (2) the transfer of land to a conservation organization associated with deed restrictions; and (3) the use of conservation easements (US) or covenants (Australia) that protect biodiversity gains on private property, and facilitate any management and/or activity

Table 1. Summary of the specifications of temporal duration for offset recruitment and retention phases from leading offset policies and guides

Duration of the recruitment phase	Duration of "long-term" and/or the retention phase	Duration of perpetual retention
United States: wetland mitigation rules under the Clean Water Act		
Until the performance standards have been met and monitoring requirements have been fulfilled	the period following the recruitment phase; in practice, 10- to 50-year time frame; alterations to compensatory mitigation projects permitted on public land in case of incompatible uses, if provision of alternative compensatory mitigation	forever (easements in some states); legal discussions regarding the perpetual nature of easements
Australia (federal): EPBC Act offset policy		
Case-by-case approach	for at least the full duration of the impact; impact on federal offset sites permitted if provision of a new offset package	N/A
Australia (Victoria): private land offsets		
10 years	beyond 10 years	forever (covenants applied in perpetuity, yet subject to mineral exploration and mining exemptions)
Australia (New South Wales): on-title biodiversity stewardship agreement		
20 years (can be extended)	beyond 20 years	forever (deeds applied in perpetuity)
France: first- and third-party offsets		
Case-by-case approach; for infrastructure projects, the duration of the concession contractually determines the maximum duration of the offset obligations (25–30 years); third-party offsets: agri-environmental schemes usually renewed every 5 years, with longer contracts being discussed	legally, as long as the impacts remain; in practice for infrastructure projects, bound by contractual offset obligations, unless the site is granted some form of public conservation protection, or benefits from an environmental real obligation on private land (99 years maximum)	perpetual contractual engagements prohibited by law
France: first four pilot supply offsets (compensatory natural sites)		
30 years (active management)	no contractual obligations for active restoration, yet various solutions proposed to pursue the ecological objectives of the sites beyond 30 years	N/A
Germany: compensation pools		
25–30 years (active management, under the responsibility of those who caused the damage)	the period following the active management phase	ideally should permanently protect sites and measures
UK DEFRA leading Pilot Offset projects (Essex and CSWAPO)		
N/A	20–25 years (long-term management)	no definition (Essex) or "a minimum of 30 years" (CSWAPO)
The European REMEDE Toolkit		
N/A	N/A	50–75 years
The World Bank's biodiversity offsets user guide		
Case-by-case basis, with the proponent supporting the up-front investment costs of the offset site	at least the operating life of the original project and ideally longer, with the proponent responsible for the first few years of the recurrent offset costs only	forever (funded via public conservation funding, philanthropy, or other non-additional funding)

In many jurisdictions, diverse types of offsets and offset mechanisms may be deployed within an offset scheme. Here, we only report the cases where offset schemes or some of their mechanisms specify or imply specific temporal durations for offset recruitment and retention. Many schemes tend to conflate the long-term with the retention phase, with limited specification of what long-term means. See Table S2 for references.

restrictions in perpetuity, meaning legally (in Common law) and literally forever.[56,57] Yet, perpetual protection may not be always perpetual in practice. There may be significant resourcing shortfalls, arrangements may be subject to exemptions, and management and monitoring may be non-existent in practice, and non-compliance can go undetected[53,57,58] (Table 1). The feasibility of

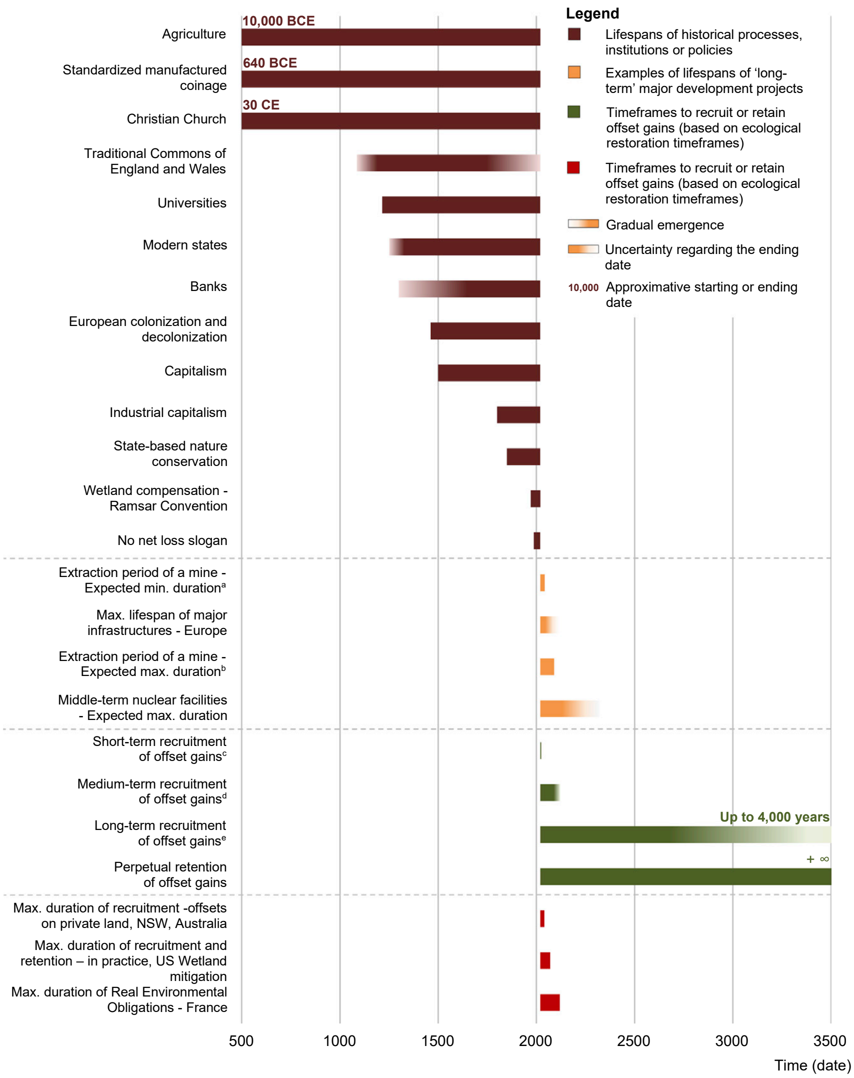

Figure 2. A comparison of time frames to recruit and retain gains with historical lifespans of Western institutions, and the expected lifespans of development activities and offset policies

See Table S5 for the numerical details and references. [a]Minimum duration of the expected extraction period of a metallurgical coal mine, corresponding to the shortest expected duration across included commodities as of 2012. [b]Maximum duration of the expected extraction period of a copper mine, corresponding to the longest expected duration across included commodities as of 2012. [c]The time frame presented being the establishment of ecosystems with fast growing species, such as eutrophic ponds. [d]The time frame presented being the restoration of ecosystems with fast and slow-growing species, such as heathlands. [e]The time frame presented being the restoration of highly degraded ecosystems dominated by slow-growing woody species, such as ancient woodlands.

long term and in perpetuity protection of offset sites also depends on the legal and customary norms regarding property rights, contractual obligations, and land management in different jurisdictions. For example, France, a Civil law country where perpetual contractual engagements are illegal,[59] has introduced Environmental Real Obligations that, once established, can bind and guide private landholders in their land-use practices for a maximum of 99 years (Table 1). Yet, these time frames may discourage landholders from engaging with offset service provisions, notably farmers given their constraints and usual reliance on short-term contracts.[60]

Ensuring effective management

Two approaches have been proposed to recruit and retain gains: offset management services and the funding of land-use transitions (Table 2, "ensuring an effective and efficient adaptive management"). In the first approach, offset service providers are paid to manage the sites to recruit the gains over a specific time period and, when relevant, continue some level of management to retain gains as long as required (e.g., long-term weed control). This is currently the most common approach embedded in leading offset policies in the US, Australia, and within Europe, where ecological consulting companies, offset "banks," private landholders, and/or the state (for example, in the case of public-land offsets) are empowered as offset service providers. Best practice literature has promoted adaptive management based on Western ecological knowledge, with plans that include performance standards and targets. More recently, in some contexts, such as Canada, traditional or Indigenous land management practices that benefit biodiversity have also become a possible form of offset services.[34] In both cases, the literature recommends to secure management practices via various management contracts or obligations, ideally included in a covenant/easement for private land, or via stewardship agreements for public land.

The second approach proposes to invest in land-use transition as a form of offset. For example, Investment Payments for Ecosystem Services have been proposed in Europe to support farmers transitioning to organic agriculture, inspired by traditional land uses that enhance biodiversity.[33] In contrast to the first approach, payments cease once the transition is complete. For farmers targeted by this approach in Europe, the costs of retaining gains then become part of the farm's ongoing business model.[33]

In both approaches, ongoing independent monitoring, evaluation, auditing, and reporting of offset gains are recommended.[4,15] Best practice literature encourages ecologists, conservation scientists, or public authorities to conduct this evaluation and provide support to offset service providers, including expertise and research. It is also argued that offset-related data should be transparent and made available on publicly accessible offset registers to improve assessment, inform public debates, ensure accountability, and enable public

Table 2. A review of the legal and institutional mechanisms used or proposed to recruit and retain offset gains based on long-term governance needs, and their identified long-term challenges

Land security	Recruitment and retention of gains	Identified long-term risks and challenges
Legally securing the gains		
• Maintaining accessible land registry records • Building social acceptability of the offset sites at the landscape level	N/A	state and civil society: costs of developing long-term institutional resilience and manage land-use conflicts, costs of offset archives and of preserving the collective memory of the sites[a]
On public land		
Binding agreements integrating offset sites to networks of publicly protected zones	land stewardship agreements with public authorities	• possibly porous boundaries between conservation and offset activities[a] • legal limitations of setting up binding contracts beyond a few decades in some jurisdictions • state: cost of reviewing and approving contracts[a]
On private land		
Covenant/perpetual conservation easement or transfer to biodiversity conservation organization with deeds restricting land uses	• inclusion of management obligation in covenants, deeds, easement, and offset services contracts • management as part of the business model for Investment ipayments for ecosystem services	• possibly porous boundaries between conservation and offset activities[a] • legal limitations of setting up binding contracts beyond a few decades in some jurisdictions • state: cost of reviewing and approving contracts[a]
Ensuring an effective and efficient adaptive management		
Ongoing adaptive management		
N/A	• long-term adaptive management plans with performance standards and targets and/or continuation of traditional land-use practices • scientific support • public access to data	• state: costs of reviewing and approving, management plans, and of making the documentation publicly available[a] • state, research bodies, and/or civil society: costs of providing support and producing scientific knowledge[a] • long-term ecological uncertainties
Monitoring on-ground practices		
N/A	• mandatory reporting • independent monitoring and evaluation • public access to data	state, research bodies, and/or civil society: costs of evaluating management, of publishing evaluations, and of legal pursuits[a]
Securing payments for services		
Securing the capital		
N/A	• appropriate budget planning for management and monitoring • fund establishment: fund established by up-front payment (preferred) or incrementally (e.g., sinking funds or revenue transfers) • fund maintenance: participation in public, or private endowment fund	• state and civil society: costs of building the expertise that can estimate intergenerational offset budgets, and the long-term institutional safeguards against the capture of capital[a] • funds: risks of losing value through time, e.g., underestimate budget, investments in risky assets, economic or Anthropocene-related shocks

(*Continued on next page*)

Table 2. *Continued*

Land security	Recruitment and retention of gains	Identified long-term risks and challenges
Securing safeguards for unexpected changes and guarantees against risks of financial or ecological failures		
Dynamic conservation easements	• multipliers (covering time lags and uncertainties) • financial surety instruments against failures of the proponent (e.g., per formance bond, surety bond, insurance bond, bank guarantees) • financial surety instruments against financial or ecological failures of the offset project (e.g., adaptable insur- ance schemes, insurance pools)	• Anthropocene-related uncertainties: failure of the surety providers, uncertain legal liabilities of retaining gains, reluctance of insurances to cover long-term environmental risks; • state: costs of establishing institutional safeguards against the instrumentalization of dynamic conservation easements[a]
Monitoring financial budgets, safeguards, and guarantees		
N/A	• fund management: independent, irrevocable, and accredited trust funds or public agencies • reporting and monitoring of investment policy, of management budget plans, and of financial surety • dedicated resources for legal defense or participation to a legal defense fund	state and civil society: cost of reviewing and monitoring financial reporting and of legal pursuits[a]

Columns 1 and 2 summarize the propositions made in the academic and gray literature devoted to offset best practices (see Table S3 for references). Many of these propositions are inspired by the experience of offsetting in common law countries and may not suit in countries with other systems of law. We did not report the propositions that violate the additionality principle in these columns. Column 3 lists the long-term risks and challenges that we have identified as overlooked while reviewing the literature.
[a]This would breach the additionality principle if conservation and offset activities are not properly differentiated and sufficiently funded.

scrutiny.[4,12,61] In practice, only a minority of countries and states have adopted consistent publicly accessible offset registers.[62,63] Little to no formal monitoring and evaluation of offsets are currently being deployed as part of offset schemes, leading to a limited evidence base for determining the efficacy of existing offset schemes.[25]

Securing payments for offset services

Legally securing gains from offsetting and ensuring appropriate ongoing management and monitoring requires secure funding over decades, and potentially more than a century, if ecological restoration time frames are considered (Table 2, ''securing payments for services''). Without secure offset funding, the longer-term costs are effectively externalized onto landholders, public and private conservation organizations, and future generations. This potentially results in crowding-out effects due to blurred boundaries between offsetting activities (intended to compensate for losses) and public or private conservation activities (intended to deliver gains).[64] This could discourage voluntary conservation efforts or, more critically, undermine the additionality of offset gains, and therefore reduce the ability of offset schemes to deliver NNL of biodiversity over the long term.[64,65]

Inspired by existing policy mechanisms, and experiences from mine closures and long-term pollution management, the best practice literature has focused on better anticipating these costs, mainly through promoting Trust Funds. Some have argued that Trust Funds should be independent and accredited, to properly track the allocation of offset funds (accountability) and avoid cost shifting, i.e., the use of offsetting funds to displace funding for conservation or other activities.[4,66] Others have recommended sufficient initial investments to create Endowment Funds, which potentially generate income as long as the stock market functions.[55,67]

Best practice reports also recommended financial surety instruments as safeguards for unexpected changes and guarantees against risks of financial or ecological failure, notably in Europe[55] (Table 2, ''securing payments for services''). Among them, environmental insurance tools are already applied to manage mining pollution risks; yet they remain relatively new, are less regulated than other types of insurance, and might be limited for projects expanding beyond 10 years.[68] The peer-reviewed literature also promotes the use of multipliers to manage risks, notably regarding socio-political uncertainties, time lags, and additionality.[69–71] Importantly, strong legal structures of checks and balances to control financial budgets, safeguards, and guarantees have been recommended, including resources dedicated to legal defense and detailed financial reporting and monitoring, in addition to independent accredited Trust Funds (Table 2, ''securing payments for services'').

In practice, the costs of recruiting and retaining offset gains remain underestimated, even for short-term time frames.[4,54] For example, in VIC, Australia, the planned budget for the recruitment of offset gains covers a 10-year management period,[72] following which offset management activities fall back on pre-existing resources. A few countries and states have introduced mechanisms to secure funding for initial management costs, as well as, in some cases, some retention costs ''for the long term.'' This includes the mandatory financial backing of ''compensatory pools'' (mitigation banks) in Germany for a minimum of 25–30 years,[73] endowment and maintenance funds for mitigation banks in the US,[32] or the Biodiversity Conservation Trust in NSW, Australia, which has set up a Biodiversity Stewardship Payment Fund aiming to provide an in perpetuity funding source.[52,74]

CRITICAL REVIEW AND PATHWAYS TO MOVE FORWARD

After identifying the approaches currently proposed and/or implemented for accruing and retaining biodiversity gains over "long" time frames, we now undertake a critical review of these propositions. In this section we first present the political imaginary that these approaches are derived from and perpetuate. We then discuss the implications of this imaginary. Each subsection below starts by identifying the major omissions and shortfalls from these approaches—and the imaginary they convey—and then ends by discussing potential ways forward.

Most of the proposed long-term biodiversity offset mechanisms apply a weak ecological modernist political imaginary to the realm of biodiversity offsetting.[3,75,76] The narratives of weak ecological modernization promote technocratic approaches (technology, markets, and management) as solutions to decouple the economy from its environmental impacts.[3,75,76] They struggle to engage with ecological limits and socio-political complexities, including deliberative democracy and the diversity of place-based bonds between local communities and the biosphere.[3,75,76]

Similarly, existing offset schemes and much of the best practice offset literature implicitly assumes that development can be decoupled from its biodiversity impact via technocratic approaches. They conceptualize biodiversity as gains that are assumed to be able to be produced over the long term by offset service markets or investments, retained on bounded offset sites and monitored by private entities, the state, and their experts. In doing so, they fail to engage with the ecological complexity and socio-political implications of this "production" (Table 2, column 3).

The polluter-pays principle and intergenerational costs

Omission

The best practice literature omits the long-term retention and governance costs needed for effective offsets. Consequently, these costs are imposed on conservation organizations, the state, research centers, and civil society.

One challenge for biodiversity offsetting is to ensure that the polluter pays the full cost of repairing the damage they cause. In the offset context this means internalizing the costs of both recruiting and retaining biodiversity gains, often over the long term. Yet, the World Bank's best practice offset guide highlights that "many developers … are only willing to support the up-front investment costs of the offset area (and maybe the first few years of recurrent costs), but not all the recurrent costs in perpetuity";[67] and thus advises that conservation resources should be relied upon for the long-term retention of gains.[67] Reliance on conservation-related institutions to pursue the ecological objectives of offset sites beyond a few decades is currently widespread (Table 1). This inevitably breaches the additionality principle (Box 1) by diverting future resources from conservation activities to the long-term retention of offset gains that, at best, have a net neutral impact on biodiversity when losses from development that generate the offsets are properly accounted for.

Furthermore, while best practice guidelines indicate that polluters should cover the long-term on-ground management and monitoring costs (Table 2, column 2), they do not engage with the governance costs that the proposed mechanisms impose on public authorities and civil society (Table 2, column 3). Institutionalizing best practice mechanisms effectively requires significant additional resources for factors, such as the controls, research, and stewardship building required by these mechanisms (Table 2, column 3). This also risks diverting resources away from conservation, as is already observed in some countries.[77]

The nuclear sector can act as a template for estimating the costs of long-term retention and some elements of the governance of offsets. For example, the nuclear industry already includes control costs and investments in research and technology in its estimation of the long-term waste management costs, to be paid by nuclear waste producers in some contexts.[78] Taxes on nuclear facility installation have also been used to fund additional research and studies in France;[79] and fees have already been introduced in Sweden to cover the costs of historical nuclear waste production.[80] Various institutional arrangements exist in leading countries to ensure that nuclear polluters contribute to covering the funding of public agencies, trusts, or companies dedicated to long-term management of nuclear waste.[79–81]

Making the polluter pay remains both a technical and governance challenge in both nuclear and extractive sectors. Costs can be underestimated when setting up the payment mechanisms due to a lack of knowledge regarding the actual long-term costs,[82] long-term economic or regulatory uncertainties,[68] or poor environmental governance and regulations.[83,84] Nevertheless, payments can be readjusted across time to correct past misestimates.[80] Importantly, initial investments or regular payments can also be disputed or purposely underestimated when both the proponent and public authorities embody a preference for the present and refuse to adopt costs, payments, or long-term financial assurances that would question the financial feasibility of a development project.[68,79]

Ways forward

Investments that are robustly additional to current conservation efforts are required to expand the control, research, and stewardship capacities of the state and civil society. These investments could be internalized in the costs of biodiversity offsetting, by potentially adapting methods and mechanisms already applied in other long-term sectors (e.g., nuclear and extractive activities). For target-based offsets, compensation ratios—proposed for some economic sectors to contribute toward biodiversity targets on top of compensating for a given project[36]—could also be used to recover the costs of historical impacts on biodiversity, or to correct past misestimations. Structural governance changes are needed to overcome the preferences for the present that undermine the polluter-pays principle. Appropriately pricing offsets with long-term costs and financial assurances would serve as a price signal to indicate that development projects that cause irreversible biodiversity loss and intergenerational injustices are too high a cost to be approved. Internalizing the long-term consequences of present-day decisions could enable a greater emphasis on project renouncement, considering alternatives, and enacting the avoidance step of the mitigation hierarchy.

Grappling with dynamic ecosystems in the Anthropocene

Omission

By conceptualizing biodiversity as a fixed entity that can accrue gains, current best practice approaches to offsetting do not engage with the dynamic dimension of ecosystems over the long term, nor the ecological and legal implications of the Anthropocene (Box 1).

Ecosystems are dynamic and subject to natural (e.g., speciation) and human-induced environmental change that can result in systems that comprise ecological novelty with no historical analogue.[85] The ecological time frames involved, coupled with the Anthropocene, bring into question the capacity to recruit and retain equivalent gains because of possible major shocks from extreme climate events and other landscape changes caused by human-induced climate change, or the direct anthropogenic drivers of biodiversity depletion. Therefore, while the objective of offset sites is to achieve NNL of specific species or ecological communities, this may not be ecologically feasible. Over longer time frames—particularly in view of the effects from anthropogenic climate change—recruited biodiversity gains on offset sites may no longer be directly comparable to the surrogate and corresponding ecosystem type that were lost, potentially becoming a hybrid or novel ecosystem.[85,86]

These ecological uncertainties have legal implications that may undermine the institutional capacity to secure compliance. Landscape changes may threaten the legal liabilities of service providers to recruit or retain accrued gains. While insurances are proposed to mitigate liability risks (Table 2, "securing payments for services"), some of the risks of failure may become uninsurable due to climate change and the increase in frequency of extreme weather events (for a discussion on possible consequences of climate change on insurances in general, see Wouter Botzen[87] and the Reserve Bank of Australia[88]). In the US, some have proposed more flexible legal arrangements, such as applying the Charitable trust principles to perpetual conservation easements[89] or establishing dynamic conservation easements to secure new offset sites if values on the original offset sites have degraded.[90]

Ways forward

The best practice literature needs to better engage with the dynamic dimensions of recruited gains. For example, the potential effects of anthropogenic climate change need to be addressed at the forefront of discussions on offset projects and their management plans, not as an afterthought. In addition, further ecological research is needed to clarify within which time frames, and under which conditions, biodiversity surrogates legally subject to offsetting in different jurisdictions can be recruited and retained over time, considering the ecological uncertainties imposed by climate change, and more broadly, the Anthropocene. This research could help assess the feasibility of reaching NNL for different surrogates and clarify which projects would likely result in a net loss of biodiversity, despite offset efforts. Further research is also needed in different jurisdictions to clarify the legal liabilities of offset service providers in rapidly changing landscapes. While some more flexible arrangements might be promoted to engage with long-term ecological uncertainties, strong institutional safeguards need to be built to avoid their instrumentalization for short-term land-use interests. For long-term or permanent offsets, collective reflections are also needed regarding how offset sites can support the dynamic and varying processes of biodiversity.

Governing for the long term in the Anthropocene

Omission

Current offset schemes and best practice guidelines are shaped by and for current Western politico-economic systems. They struggle to consider time horizons beyond 50–100 years and consequently are ill-prepared for the institutional implications of governing offset gains for the long term.

Current Western politico-economic systems, including capitalist economies and modern representative democracies, are not structured to consider the consequences of present-day decisions on the long-term future (over one or more centuries).[26] More fundamentally, modern liberal democracies, born in Europe, have constructed themselves through the rejection of European traditions and the idea that the present should be sacrificed for future salvation.[27]

Blind to long-term concerns, they are structurally driven by cultural, economic, and political stochastic changes, responding to financial time frames, political cycles, and planning forecasting that vary from the very short term (a few months to a few years) to the short term (up to 20 years), from an ecological standpoint (Figure 1). This preference for the present is embodied, for example, in the continuous extension of temporary storage for high-level radioactive waste resulting from the operation of commercial nuclear power plants in many countries since the 1950s, and the absence of countries with an operating deep geological disposal facility, albeit the recent progress in Finland and Sweden.[82,91] Biodiversity conservation has also been shaped by these institutional time frames. Long-term research and on-ground restoration projects rarely expand beyond 10–15 years.[92–94] It is thus not surprising to find similar institutional time frames in current offset policies and guidelines (Table 1; see also Figure 2, rows 14–24, for a few examples).

Ecological time frames necessary to recruit and retain biodiversity gains for some complex offset surrogates reach the time frames of historical periods or potentially even civilizations, if they are to account for permanent loss of some components of biodiversity (Figure 2). Furthermore, it is likely that the Western politico-economic systems and their key institutions (i.e., markets, the state, and expert bodies) will experience significant transformations or even disappear within the time frames required to recruit or retain these complex offset gains. Human institutions are not static entities—they emerge, evolve, merge, and disappear. The Western institutions that gave birth to the current Western politico-economic systems (Figure 2, rows 3–11) are relatively young from an ecological perspective. Other institutions are older—many Indigenous and traditional cultures across the globe have long-established and resilient institutions, some of which have successfully protected sacred natural sites and sustainably governed common-pool natural resources for centuries, and in some cases, for millennia.[95–100] Yet, these institutions often continue to be disregarded, marginalized, or undermined by Western formal institutions, and the field of conservation.[99–103]

Institutional changes are also likely to accelerate with the unfolding of anthropogenic environmental shocks (such as severe anthropogenic climate events or biosphere disruptions) as societies are forced to undertake transformative institutional changes or experience major unpredictable instabilities in existing social-ecological systems.[104–106] Such changes have already been observed: some institutions are adapting,[99] new forms of governance and institutions are emerging,[107] and new informal, collaborative actions are being deployed outside formal Western institutions.[108]

Despite this changing long-term context, the offset literature proposes mechanisms that are highly reliant on current formal Western institutions, implicitly assuming the future stability of these relatively young institutions over the long term. We argue that this assumption is unreasonable for long-term and perpetual offsets and might also become unreasonable under shorter time frames because of accelerating instabilities due to the Anthropocene. For example, severe economic recessions can consume the principle of secured funds.[68] More extreme shocks (due to, for example, severe climatic events, global pandemics, or wars) may also threaten the capacity of the modern state or markets to function, and even the potential collapse of Western global civilization is currently being debated.[109,110]

Ways forward

Supporting changes in offset policies that incorporate multidecadal and century-plus time frames would be a step forward. Yet, solely relying on short-lived Western institutions to secure the long-term governance of offset gains remains risky. In our view, the offset literature, policies, and practitioners could better engage in how to improve the resilience (Box 1) of offset-related institutions. Genuine, rather than instrumental, discussions between formal offset-related institutions and long-lived, resilient Indigenous and traditional governance systems could contribute to facilitating the long-term recruitment and retention of biodiversity gains. For example, offsets could be integrated into existing long-lived Indigenous and traditional social-ecological institutions. However, care needs to be taken to ensure that the additionality and polluter-pays principles are maintained, and that offsets do not destabilize these complex institutions. In addition, deeper structural reforms are required for long-term concerns and long-term governance to be considered in formal Western institutions, democratic debates, and deliberations across scales, notably when planning and development proposals are discussed (for propositions, see Rosanvallon,[27] Bourg,[111] and Takacs[112]). In many contexts, engaging with Indigenous and traditional norms, knowledge systems, institutions, and land rights claims should be essential in these structural transformations.[99,102,103]

The socio-political dimension of offset governance

Omission

Relatively few sources in the offset literature have grappled with the socio-political complexities of governing offset gains. Considerations discussed in the literature solely include how to better engage stakeholders in the offsetting process, "building acceptance" and maintaining good relationships with properties surrounding offset sites.[12,53,113]

The imaginary embedded in offset best practice literature risks repeating some of the past mistakes of the conservation field, which historically framed nature as "wild" objects that could be locked in bounded parks, placed under the control of experts and away from local communities.[114] Despite progress, the conservation field continues to struggle with engaging the human dimension of conservation—notably with formal, informal, and customary rules, social practices, power dynamics, forms of knowledge, values, place-based social-ecological relations, and complex politics across scales.[107,115,116] Similar struggles were observed in the offset literature. Yet, these socio-political dimensions are yet to be seriously addressed. For example, human conflicts over land use and access to natural resources are affecting biodiversity and its conservation;[117] protected areas, while promoted as the strongest form of protection over the long term,[118] have seen their protection status being degraded in some contexts[119–121] and their achievements being affected by human activities in their surroundings.[122] Perpetual conservation easements have already been challenged under development pressures in the US.[56] It is to be expected that offset sites risk experiencing similar challenges that could, if not anticipated, lead to the loss of recruited gains.

Ways forward

Approaches to the governance of offset sites must be expanded to build in the long-term stewardship of offset gains and to prepare for potential future land-use conflicts. We encourage the field of offsetting to collaborate further with social scientists and the humanities, public authorities, Indigenous peoples, and civil societies to accelerate transfer of the lessons already learnt regarding social-ecological resilience, democratic deliberation, and conflict management. The many learnings within conservation (and beyond) that could be applied, include conflict resolution and collaborative governance,[117] common-pool resources management,[101,123] stewardship,[124] values,[125,126] justice,[127] ecological democracy,[112] partnerships between different knowledge systems,[103] and biocultural diversity.[8] The use of deliberative platforms could enable communities and societies to explicitly discuss and refine the knowledges, actors, and institutional rules to be deployed to retain the recruited offset gains. This could help societies anchor the offset sites within their social-ecological landscapes and institutions, manage conflicts between actors, and adapt to social-ecological changes across time. Importantly, efforts to build these platforms or adapt existing ones need to be additional (yet, potentially complementary) to conservation, with their costs being factored into the estimation of offset costs.

CONCLUSION

We present an analysis of biodiversity offsetting mechanisms proposed by the best practice literature, and in use by current offset schemes, to govern offset gains over long-term time frames. While current governance mechanisms are theoretically tailored for biodiversity gains to be recruited and retained over a few years to a maximum of a few decades, these time frames do not match most ecological time frames needed to reach NNL. In practice, many offsets are likely to require governance for over a century, and in some cases, millennia, to recruit and retain biodiversity gains that offset the equivalent (significant and often permanent) biodiversity losses. However, the time frames that current Western institutions operate under, on which offsets are based, cannot ensure the longevity of these institutions. Therefore, we recommend initiating a process of incorporating long-term considerations in offset policies and of building institutional safeguards to ensure that the polluter-pays principle is properly applied to offsetting; factoring in the long-term retention, governance, and stewardship costs into the payments to be paid by the polluters. Finally, we argue that offsetting should not be discursively sold by default as delivering NNL. In our view, current NNL approaches, at best, temporarily reduce permanent damage by making polluters partially accountable for their impacts and by providing clear targets to operationalize offsets in the short to medium term. At worst, current approaches to offsetting participate in a false promise, which distracts institutional efforts from much needed transformative change centered on renouncing impactful projects, considering a greater range of alternatives, and a greater emphasis on avoidance in the mitigation hierarchy.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to the corresponding author, Florence L.P. Damiens (florence.damiens@rmit.edu.au).

Materials availability

All sources used in this Perspective are listed in the References or in the Supplemental information. All sources were publicly available at the time of the analysis; however, most academic publications are behind journal paywalls.

Data and code availability

All data and sources used to produce Tables 1 and 2 and Figures 1 and 2 are available in the Supplemental information. Figures 1 and 2 were generated in Excel and PowerPoint, Version 2011.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2020.12.012.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.G., F.L.P.D., and A.B.; investigation and visualization, F.L.P.D.; writing – original draft, F.L.P.D.; writing – review & editing, F.L.P.D., A.G., and A.B.

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Quantifying peatland land use and CO_2 emissions in Irish raised bogs: mapping insights using Sentinel-2 data and Google Earth Engine

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Ireland has > 50% of the EU's ocean-raised bogs; however, degradation through land-use activities has transformed them from carbon (C) sinks to sources. Given their significant role in climate mitigation, it is essential to quantify the emissions resulting from land use degradation of these ecosystems. A seven-class land-use classification system for Irish peatlands (LUCIP) was developed and mapped using Sentinel-2 imagery, random forest machine learning and Google Earth Engine. The results revealed that agricultural grassland comprised 43% of the land use on raised bogs, followed by, forestry (21%), cutover (11%), cutaway (10%) remnant peatlands (13%), waterbodies and built-up ~ 1% each. The overall accuracy of the map was 89%. The map was used to estimate CO_2 emissions for four classes constituting 85% of raised bogs: cutover, cutaway, grassland, and forestry using the IPCC wetlands supplement and literature-based emission factors, we estimated emissions at ~ 1.92 (± 1.58–2.27 Mt CO_2-C-yr^{-1}) and ~ 0.68 Mt CO_2-C-yr^{-1} (± 0.44–0.91 Mt CO_2-C-yr^{-1}) respectively. This is the first study to spatially quantify land use and related emissions from raised bogs. The results have revealed widespread degradation of these globally rare habitats, making them net emitters of CO_2. The map is vital for the conservation of these ecosystems through restoration efforts, and the methodology can also be applied to other regions with similar peatland land use issues.

European peatlands cover approximately 60 million ha[1,2], and a substantial proportion of this has been degraded by unsustainable land use practices, such as agriculture, forestry, and peat extraction. Consequently, almost 44% can no longer accumulate peat[3]. Tanneberger et al.[4] indicated that degraded peatlands in the European Union (EU) represent half of the globally degraded peatlands. In Ireland, peatlands cover ~ 1.46 million ha (21% of Ireland) and consist of two types of bogs: blanket bogs (~ 900,000 ha) and the globally rare Oceanic raised bog (~ 530,000 ha)[5,6]. It is estimated that they store between 60 and 75% of the national Soil Organic Carbon (SOC) stock[7–9] but land use practices have led to the degradation of about 95% of these peatlands[6,10–13].

These land use activities harm the hydrological and ecological functioning of peatland ecosystems, turning them from a net sink to a source of C[14]. It also results in a consistently lowered water table, which accelerates peat decomposition, releases dissolved organic carbon (DOC) and particulate organic carbon (POC) and alters carbon and greenhouse gas (C and GHG) fluxes[15,16]. Hence, these ecosystems, which in their natural condition are significant C stores and are crucial to the prevention of natural disasters such as landslides, fires, and floods[17], become susceptible to them[18–20]. Despite this, Irish peatlands still contribute to various hydrological and ecological functions and cultural, and socio-economic values[6,21].

The land use practices on peatlands in Ireland are similar to those in Europe, including drainage for industrial and domestic peat extraction, agriculture (mostly grasslands), afforestation and infrastructure development (roads, wind farms, airports etc.)[12,22,23]. As a result, it is estimated that less than 1% of raised bogs in Ireland are actively forming peat as of 2017[24]. This is particularly due to the intensification of land use through industrial peat extraction, afforestation and agriculture, which is a relatively recent development (since the 1940s), but has caused more damage in a short period of time[22]. The establishment of Bord na Móna (BnM), a semi-state-owned

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company, in 1946 for industrial peat extraction had a notable impact on raised bogs. Approximately 90% of the BnM landholdings are situated on raised bogs, and the majority of those (~ 90%) have been drained and/or opened for peat extraction[62]. BnM ceased extraction activities in 2021[25], however, there are still several medium-sized companies engaged in industrial peat extraction, including Harte, Klasmann-Deilmann, Bulrush, Clover, Erin, and Westland, as well as ~ 30 other small producers[11,14]. Coillte, a semi-private afforestation company established in 1989, has afforested approximately 31,000 ha of raised bogs. The provision of grants through the Common Agricultural Policy (CAP) for the reclamation of raised bog edges for agriculture has also contributed to the intensification of land use in these ecosystems. However, spatially explicit data on the extent of these activities (especially non-BnM industrial activities) and domestic peat extraction activities is non-existent[26]. The absence of such data prevents accurate quantification of emissions from managed peatlands and hinders the formulation of effective conservation strategies.

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), Ireland has an obligation to report and account for its GHG emissions and removals and meet its emission targets for Land Use, Land Use Change, and Forestry (LULUCF), including wetlands, as outlined in the EU's 2030 climate change framework[27]. Several studies have been conducted on Irish raised bogs at small spatial scales to gain insights into the effect of land use conversion activities on C and GHG dynamics, such as losses through land, atmospheric, and fluvial emissions[28,29]. These local-scale effects can have regional and global consequences; yet information on land use status and associated emissions from these ecosystems remains poorly understood at the national, regional, and global levels[30]. To propagate local-scale emission measurements to a national scale and accurately account for peatland emissions, spatially explicit information on peatland land use is essential[14,26]. Andersen et al.[31] emphasise the importance of land use/cover data in understanding degradation and restoration. However, national and global land-use/cover maps often exclude activities such as peat extraction, forest and abandoned peat extraction sites[4]. This makes these datasets inadequate for understanding degradation through land use, monitoring conservation activities (rehabilitation, restoration, and rewetting), and assessing C and GHG emission dynamics.

To report emissions from wetlands, the Intergovernmental Panel on Climate Change (IPCC) has proposed a system consisting of three tiers: Tier 1 (T1) includes default EF and is specifically for wetlands and Tier 2 (T2) EFs are country specific and based on the emission data from case studies. The Tier 3 (T3) EFs use more complex and dynamic models. The default T1 EFs are derived from limited data available from sites with different geographical, climatic, and ecological conditions. Ireland reports emissions from peatlands based on T1 EFs except for industrial peat extraction sites and forests on drained peatlands, where country-specific EF values are being used[32]. However, the reliance on coarse spatial resolution (25 ha) CORINE (Co-ordinated Information on the Environment) land cover data and non-spatially explicit information for reporting purposes make the national emission estimates less accurate. Given these limitations, it is essential to develop peatland-specific land use maps that can be used for more accurate upscaling of emissions from site to regional, national, and global scales using IPCC methods. Furthermore, these maps are vital for supporting conservation activities, sustainable land management practices, and policy-related decision making.

This study aims to map the much-needed spatial distribution of land use on raised bogs in Ireland and quantify the corresponding C and GHG emissions[5,33,34]. The spatial extent of raised bogs was based on the DIPMv2 (Derived Irish Peat Map version 2), which is the latest peatland extent map integrating data from multiple sources[5]. Spatially explicit information on land use can be obtained using remote sensing methods. However, the persistent cloud cover inherent to the temperate maritime climate of Ireland poses a challenge to the acquisition of frequent cloud-free optical remote sensing images[36]. Consequently, it is particularly difficult to map national-scale land cover and land use. Previous attempts to map land cover at a national scale in Ireland have encountered similar difficulties and full coverage has not been achieved[36–39]. Connolly[12] successfully mapped industrial, grassland and forestry on peatlands in Ireland, including raised bogs, but was unable to map domestic peat extraction, because of medium spatial resolution of the data (23 m) and cloud cover issues.

Google Earth Engine (GEE), a planetary-scale cloud computing platform[40], integrates freely available high-resolution satellite imagery such as Sentinel-2, as well as machine learning algorithms such as random forest. By leveraging a vast archive of satellite imagery and employing temporal mosaicking functions within GEE, it is possible to obtain cloud-free imagery with wall-to-wall coverage and use it to map land use in areas where cloud cover impedes optical remote sensing[41–43]. This approach was used in this study to obtain cloud-free imagery by mosaicking annual images acquired for three years i.e., from 1st January 2018 to 31st December 2020. As a result, the first national-scale land use map of raised bog with seven classes was developed. The classes were derived from the Land Use Classification of Irish Peatlands (LUCIP), which was developed for this study through discussions with various stakeholders including NPWS (National Parks and Wildlife Service), BnM, and an ecologist. The classes in LUCIP includes cutover, cutaway, grassland, forestry, remnant peatlands, water bodies, and built-up areas. The map enabled the assessment of the spatial extent of land use in raised bogs. It is further used to estimate CO_2 emissions using site-specific EFs from case studies in Ireland[26], which are then presented along with IPCC T1 EFs. This work will provide better insight into C dynamics at the site scale, with an emphasis on the importance of high-resolution maps for area estimation and country specific EFs.

Material and methods

Study area

The study area for this research was based on the spatial extent of raised bogs derived from the DIPMv2[5]. Raised bogs are predominantly situated in the midlands of Ireland and are a distinctive feature of this inland region. They cover ~ 530,000 ha of the surface area and constitute ~ 35% of the total peatland area in Ireland and 8% of the total land surface area. Irish raised bogs represent more than 50% of oceanic-raised bogs in the EU[35].

Satellite image data

Copernicus Sentinel-2-MSI (Multi-Spectral Instrument) optical remote sensing satellite images were used in this study and the images were acquired by Sentinel 2- A and B. The Sentinel-2 sensor has 13 spectral bands, 10 of which were used in this study: Red (R), Green (G), Blue (B), Near Infrared (NIR) and Narrow NIR, three of the Vegetation Red Edge, and two of the Short-Wave Infrared (SWIR)[44]. Table 1 shows the spectral and spatial resolutions of the bands used in this study. The RGB and NIR bands have a spatial resolution of 10 m while the rest were resampled from 20 to 10 m. The sensor has a swath width of 290 km[44].

GEE provides the Sentinel-2-MSI Level-2A (L2A) image archive dating back to March 2017. This study used the atmospherically corrected products:L2AS2_SR (Sentinel-2 Surface Reflectance). They are corrected for atmospheric, slope and adjacency effects. L2A processing is based on a two-step process i.e., (1) scene classification (SC), which is used to derive a pixel classification map for vegetation, snow, soil, cloud shadows and cloud and (2) Sentinel-2 Atmospheric Correction (S2AC) which is used to convert the Top of Atmosphere (TOA) reflectance to BOA (Bottom of Atmosphere) values. The S2AC process is based on the library for Radiative transfer (libRadtran) model[46,47]. It provides cloud, haze, and water removal methods. To enhance the classification process, the vegetation and water indices were calculated and included as additional bands. The Normalised Difference Vegetation Index (NDVI) with values ranging from 0.1 to 1 indicates the presence and health of vegetation[48] (Eq. 1), while the Normalised Difference Water Index (NDWI) with values ≥ 0.5 indicating the presence of open water[49] (Eq. 2).

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

$$NDWI = \frac{NNIR - SWIR1}{NNIR + SWIR1} \tag{2}$$

Image classification methods

A remote sensing image classification-based approach was used in this study and implemented in GEE and ArcGIS Pro desktop version 2.7 (ArcPro from here onwards). The approach consisted of accessing, pre-processing, and classifying land use using LUCIP in GEE. Accuracy assessment was conducted using ArcPro. The imagery was accessed on a national scale and constrained to Irish-raised bogs using the DIPMv2. An overview of this process is shown in Fig. 1.

Image pre-processing

Despite the high temporal resolution (five days) of Sentinel-2 (A and B), obtaining a cloud-free mosaic for wall-to-wall coverage of raised bogs in Ireland was challenging. To address this, it is important to develop an efficient cloud removal methodology. Accordingly, a temporal filter was applied to obtain imagery over three years (1st January 2018 – 31st December 2020). A selection criterion to obtain images with less than 10% cloud cover was also applied; a percentage greater than this would return cloud-contaminated images that were not useful for analysis. Based on these criteria, 1483 images were available. The remaining cloudy pixels were masked out using a cloud masking function (*masksS2clouds)* which is based on the 'QA60' quality flag band used for cloud and cirrus. Finally, the images were stacked together to generate a single cloud-free composite using the median (*ee.reducer*) composite function available in GEE. This also helped eliminate pixels with extreme values, thus removing the remaining artefacts. The final image was composed of pixels with minimal or no cloud cover.

Training sample data

The training and validation data used in this study were independent of each other. The training data was based on randomly generated sample polygons created within GEE for each land use class (Table 2). Validation sample points were generated using ArcPro. A classification schema (LUCIP) was developed to identify seven land-use

Bands	Central wavelength (µm)	Spatial resolution (m)
Band 2—Blue	0.490	10
Band 3—Green	0.560	10
Band 4—Red	0.665	10
Band 5—Vegetation red edge	0.705	20
Band 6—Vegetation red edge	0.740	20
Band 7—Vegetation red edge	0.783	20
Band 8—NIR	0.842	10
Band 8a—NNIR	0.865	20
Band 11—SWIR	1.610	20
Band 12—SWIR	2.190	20

Table 1. Characteristics of sentinel-2 bands[45].

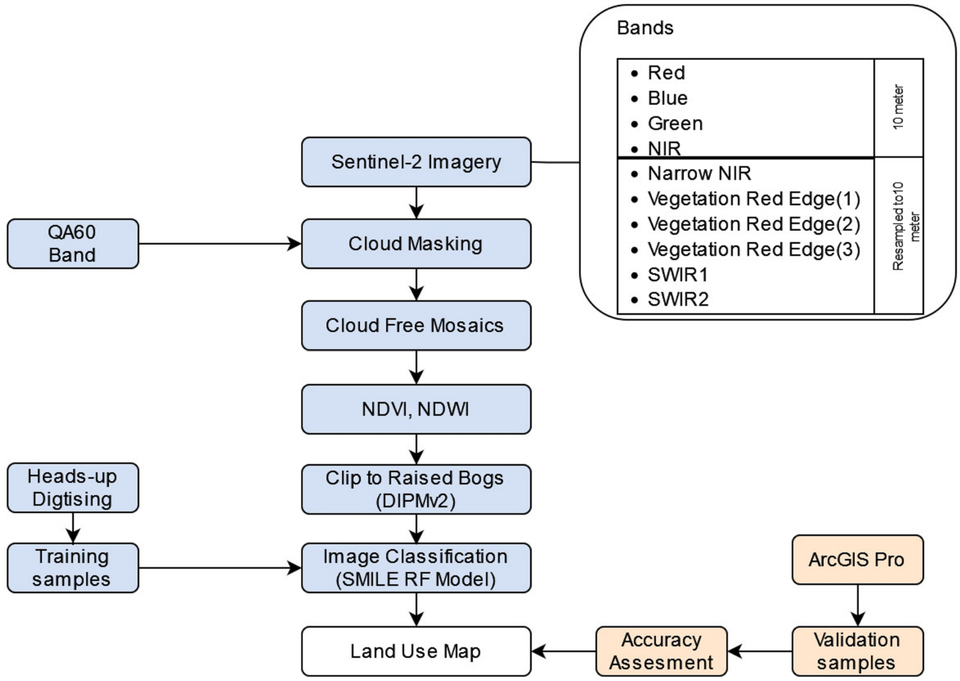

Figure 1. Data processing workflow. NIR (Near Infrared), SWIR (Shortwave Infrared), NDVI (Normalised Difference Vegetation Index), Normalised Difference Water Index (NDWI), QA60 (Quality Assessment) band for cloud and cirrus masking, and DIPMv2 (Derived Irish Peat Map version 2).

Land use class	Description
Cutaway	Land that has been subjected to industrial peat extraction, with the peat removed and/or left with a thin layer of soil, managed by BnM and other private companies with large-scale mechanised peat extraction.
Cutover	Land that has been subjected to domestic peat extraction, hand-cut, small-scale mechanised, includes bare peat, interspersed woodland, heath, and scrub.
Grassland	Agriculture grassland that is used for pasture or hay, silage, and grazing.
Forestry	Land covered with trees; afforested areas are mostly covered by evergreen tree species
Remnant Peatland	Land that has a high percentage of peat (near natural and high bog areas,) and is characterised by the presence of sphagnum mosses and other bog flora, not directly affected by human intervention. Revegetated areas of post-extraction activities.
Water bodies	Land covered with water, including natural waterways and surface water on raised bogs that have appeared after rewetting activities and/or abandonment.
Built-up/Infrastructure	Land used for human settlements and infrastructure, such as buildings, roads, windfarms etc.,

Table 2. Description of land use classes based on Land Use Classification for Irish Peatland (LUCIP) developed in this study.

classes: cutover, cutaway, grassland, forestry, remnant peatlands (high bog), and built-up/infrastructure areas (Table 2).

The collection of training data was based on the visual interpretation technique, which was used by an expert operator to generate randomly distributed sample polygons for each land use class[50]. The training data consisted of 366 polygons (148405 pixels) that were randomly distributed across the study area (Table 3).

The spectral signature of each land use class is shown in Fig. 2. The mean reflectance values across multiple Sentinel-2 bands demonstrate significant spectral separability in the visible and NIR range i.e., 0.49 to 0.78 µm. Notably, built-up areas exhibit high reflectance, whereas water has low reflectance, making them significantly distinguishable. Cutaway and grassland show high reflectance in the NIR region. Cutover and remnant peatlands, however, may exhibit some similarities, given that the cutover class includes dynamic vegetation environment. The spectral separability for most classes diminishes for longer wavelength bands, specifically at 1.61 and 2.19 µm. Nevertheless, differences in spectral reflectance between all the classes remain prominently discernible, underscoring the effectiveness of the sampling procedure employed for land use classification.

Land use class	No. of training polygons	No. of training pixels (sum per training polygon)	No. of validation points
Cutaway	37	94,672	197
Cutover	45	4345	130
Grassland	32	7320	660
Forestry	100	11,627	252
Remnant Peatland	62	28,038	121
Water bodies	64	1816	50
Built-up/Infrastructure	26	587	50
Total	366	148,405	1460

Table 3. Characteristics of randomly distributed training and validation sample data.

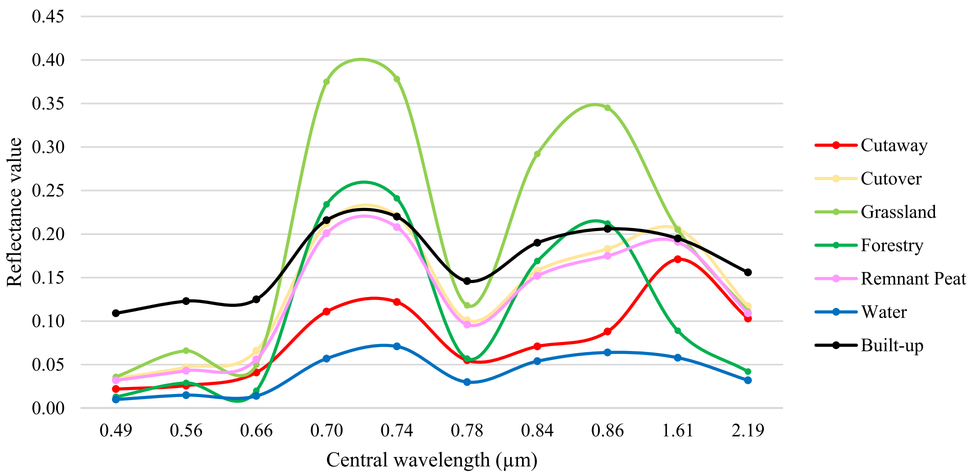

Figure 2. Spectral reflectance of the land use types across the ten spectral bands (Sentinel-2).

Classification of satellite imagery

The random forest classification model, an ensemble classifier[51,52], was trained using training data. The random forest algorithm is based on an ensemble of several decision trees, each with multiple nodes[51]. Classification was implemented using the GEE platform. A slightly improved version of the random forest model known as the Statistical Machine Intelligence and Learning Engine (SMILE) random forest algorithm was used in this study[53]. The classification model was trained using the training data, with the number of variables and number of trees being the two critical parameters. The optimal values of these parameters were determined using the square root of the number of features and trial-and-error method. Based on these procedures, the optimal number of trees was determined as 20. Each tree in the model consists of multiple nodes, and each pixel is assigned a label by each tree. The final label for each pixel is determined by aggregating the labels assigned by all trees through a majority vote[51]. The random forest model and its optimisation procedures were implemented using the GEE. The variable importance for all spectral bands, NDVI, and NDWI were also assessed. Spectral reflectance bands (2, 5, 12, and 11) were ranked higher, while NDVI and NDWI were ranked lower (see Supplementary Fig. S1 online). The accuracy of the final output map was assessed using the validation data.

Validation (accuracy assessment)

After conducting a qualitative accuracy assessment (visual evaluation), the final map was downloaded from GEE and imported into ArcPro. An overall quantitative accuracy assessment was conducted using ArcPro, with independent validation point sample data (Table 3). Yelena and Antonia[54] emphasise the importance of using higher-quality reference data derived through a sampling approach to assess the accuracy of land use maps. They further noted that the data could be based on field sampling or a higher resolution spatial resolution aerial imagery. The latter approach was used in this study since the first approach could be laborious and time-consuming for national scale mapping. The “create accuracy assessment tool” in ArcPro was used with a stratified random sampling strategy[55]. The tool generates random points, and the sample size is based on the proportion of the area for each class. This process ensures that a sufficient number of reference samples is created for each stratum (class)[55]. A total of 1460 points were obtained (Table 3). Each validation sample data point was assessed and manually labelled through the visual interpretation of very high-resolution aerial imagery (25 cm) by a single expert operator. After completion of manual labelling, a confusion matrix for accuracy assessment was generated using the “compute confusion matrix” tool in ArcPro. This was performed by comparing the classes obtained using the classification model with the ground truth data. Multiple statistics were derived from the confusion matrix to quantify the map accuracy. These include the Overall Accuracy (OA), overall agreement between classification (map), and ground truth for all classes. The User's accuracy (UA) measures the agreement between the classified pixels and the ground-truth data for a specific class from the user's perspective, whereas the Producer's accuracy (PA) measures the agreement between the classified pixels and the ground-truth data for a specific class from the producer's perspective[56]. Lastly, owing to the presence of errors in the classification results, a simple pixel counting method to calculate the land use area is not adequate. Therefore, 'good practices', as suggested by Olofsson et al.[55] were used to generate an area-based error matrix and calculate the unbiased land-use area for each class.

CO_2 emission calculations

CO_2 emissions were calculated using the IPCC T1 EFs and literature-based T2 EFs using Eq. (3). Four dominant land use classes (cutaway, cutover, forestry, and grassland), which cover ~ 85% of the total raised bog land use area (Fig. 3) were used for emission estimation. For the remaining classes (remnant peatlands, water bodies, and built-up areas), neither T1 nor T2 emission factors were available; therefore, CO_2 emissions could not be estimated. T1 default EFs from the IPCC Wetland Supplement (2013) and T2 EFs by Aitova et al.[26] which are based on case studies in Ireland for grasslands, cutover and cutaway sites were used. The EF for forestry is based on eight drained and afforested peatland sites in Ireland[57].

$$\mathrm{CO_2\ emission}\ \left(\mathrm{tCO_2 - C\ ha^{-1}y^{-1}}\right) = \mathrm{land\ use\ area\ (ha)}\ \times\ \mathrm{EF}\ \left(\mathrm{tCO_2 - C\ ha^{-1}y^{-1}}\right) \tag{3}$$

where t is tons, ha is hectares, y represents a year, and EF is the land use specific emission factor.

Results

The statistics for the area of each land use class in raised bogs obtained using the error matrix (see Supplementary Table S1 online) are presented in Fig. 3. Almost half of the raised bogs mapped in this study are covered by grassland i.e., 43% (244,100 ha). Forest covers about 21% (116,427 ha), cutaway 10% (54,302 ha) and cutover cover 11% (646,99 ha). Remnant peatlands (high bog) area covers about 13% (73,795) ha. Water bodies and built-up areas account for about 1% (1542 ha and 1358 ha, respectively). The water bodies here constitute both natural waterways included in the coarse resolution DIPMv2 and surface water on raised bog appearing possibly after rewetting activities.

The prevalence of land use activities can be seen across all raised bogs in the midlands of Ireland Fig. 4. Industrial peatland extraction sites are primarily located in the midlands (Fig. 4a) and some parts of the north (Fig. 4b and c) and south (Fig. 4f) of the midlands. Approximately 65% of these industrial extraction sites are owned by BnM. The other 35% constitute non-BnM peat extraction carried out on an industrial scale similar to BnM (Fig. 4d and e). BnM landholding and Special Area of Conservation (SAC) boundary data were used to further examine the distribution of land use to better understand the status and condition of raised bogs under different management regimes, i.e., industrial and protected (Table 4). Additionally, Coillte landholding boundary data was also used to assess land use. It owns ~ 31,000 ha of raised bog areas accounting for about one-third of the total forestry on these bogs.

The exposed peat on BnM landholdings amounts to around 42,264 ha. The rest of the cutaway bogs, totalling about 2,460 ha, are in SAC, highlighting the existence of a substantial amount of bare peat on these "protected" bogs with active cutting also taking place[58]. Cutaway bogs in midlands have interspersed forestry (Fig. 4a). The areas on the edges of these bogs represent agricultural grasslands. The remnant peatlands in the midlands and are mostly on SAC sites such as Clara Bog, Ferbane Bog, Moyclare Bog, and Raheenmore Bog (Fig. 4a). Overall, there is about 13,053 ha of the remnant peatlands located on the SAC, which is approximately 1% of the total peatland area and most of the "actively forming raised bogs" are possibly located in these sites[59]. The majority of the remnant peatlands are in the west of the midlands and are surrounded by peat-extraction activities (Fig. 4d and e). Lastly, the scattered water bodies on cutaway sites in the Midlands and some parts in the North are possible signs of some of the rewetting activities being carried out by BnM (Fig. 4a and b).

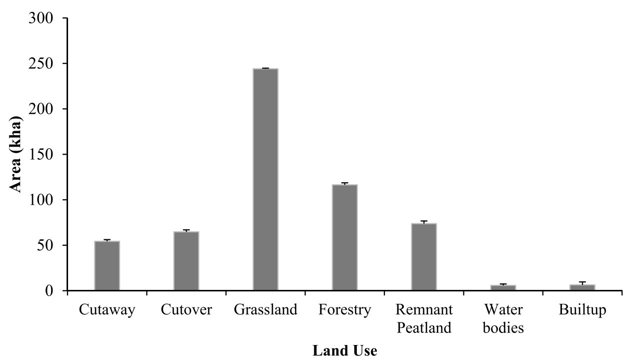

Figure 3. Land use area in kilo hectares (kha) for each class, error bars for standard errors in kha.

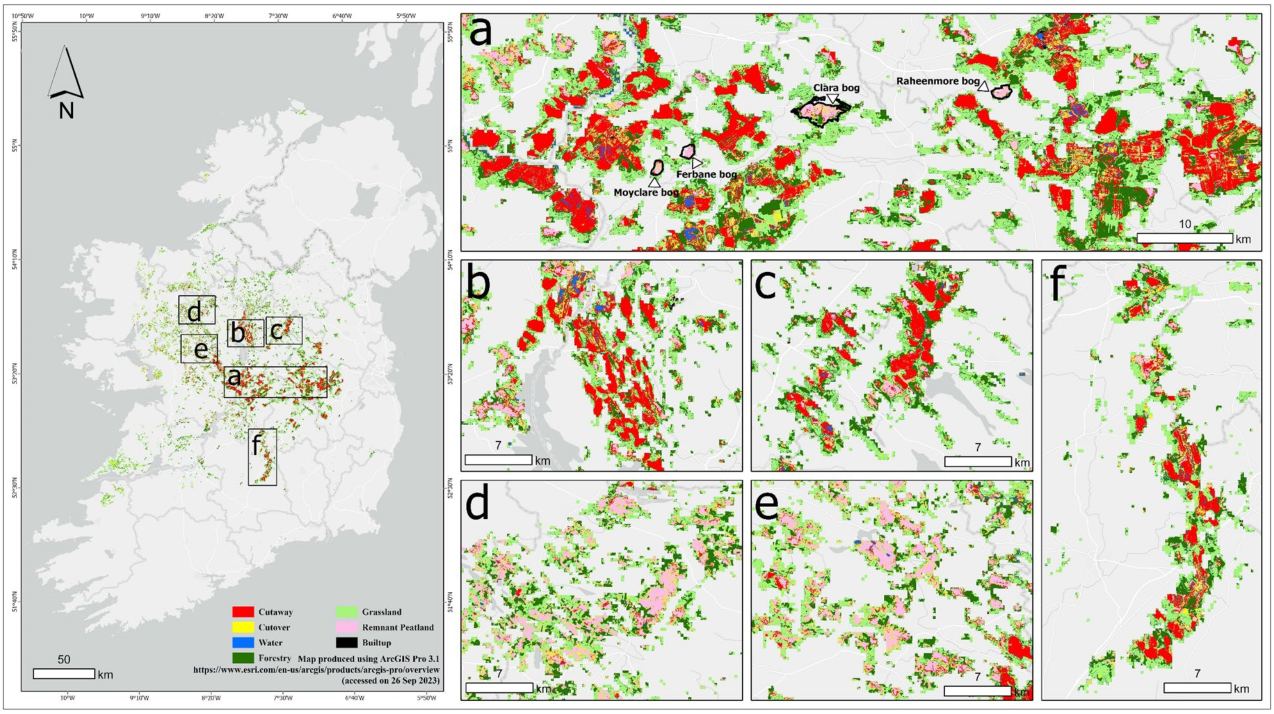

Figure 4. Land use on raised bogs. (**a**), (**b**), (**c**) and (**f**) are dominated by industrial peat extraction sites (mostly Bord na Móna), whereas (**d**) and (**e**) have a mix of remnant peatland, cutover, grassland, and forest.

Class	BnM (ha)	SAC (ha)
Cutaway	42,264	2460
Cutover	7303	4907
Grassland	2379	7318
Forestry	9067	3490
Remnant Peatland	6491	13,053
Water bodies	1580	1340
Built-up/Infrastructure	388	197
Total	69,472	32,568

Table 4. Proportion of each land use on Bord Na Mónaa (BnM) and Special Area of Conservation (SAC) under the national parks and wildlife services (NPWS). All areas are in hectares (ha).

CO_2 emissions

CO_2 emissions presented in Table 5 are calculated using Eq. (1) for the four land use classes. The area (ha) is estimated from the land use map (Fig. 4). T1 emissions were ranging between 303,710 and 1,293,730 t CO_2-C ha^{-1} y^{-1} with grassland being the highest emitters followed by forestry, cutover, and cutaway. T2 emissions were in the range of 65,705–317,330 t CO_2-C ha^{-1} y^{-1}, with the highest emissions in grassland and the lowest emissions in cutaway. The T1 emissions for grassland were four-fold higher than T2 emissions. The total CO_2 emissions

Land Use	Area (ha)	T1 (IPCC) EFs	T1 Emissions (t CO_2-C ha^{-1} y^{-1})	T2 (literature) EFs	T2 Emissions (t CO_2-C ha^{-1} y^{-1})	No. of sites for T2 EFs	References
Cutover	64,699	2.8 (1.1–4.2)	181,157	1.21 (0.4 – 2.0)	102,871	3	[26]
Cutaway	54,302	2.8 (1.1–4.2)	152,046	1.59 (1.2 – 2.0)	65,705	4	[26]
Forestry	116,427	2.6 (2.0–3.3)	302,710	1.68 (1.04 – 2.32)	195,597	8	[57]
Grassland	244,100	5.3 (3.7–6.9)	1,293,730	1.3 (0.04 – 2.55)	317,330	3	[26]

Table 5. Emissions from four dominant land use classes, with Intergovernmental Panel on Climate Change (IPCC) Tier 1 and 2 (T1 and T2) Emission Factors (EFs) with 95% confidence intervals values are shown in brackets, Emissions based on the area in hectares (ha) and EFs (in tonnes of CO_2-C per hectare per year).

from Irish-raised bogs based on the four land use classes mapped here account for 0.68 Mt CO_2-C ha^{-1} y^{-1} as per T2 and 1.92 Mt CO_2-C y^{-1} as per T1.

Accuracy assessment

The OA of the final land use map was 89% which is computed from the diagonal line of the confusion matrix (Table 6), representing the number of correctly classified classes. A total of 1303 of 1460 points were correctly classified. The UA ranges from 70% (water and cutover) to 96% (forest), and PA ranges from 64% (built-up) to 97% (cutaway).

The results show the highest PA for cutaway (97%) and grassland classes (93%) while remnant peatlands (75%) and built-up (64%) have the lowest PA. Forestry (97%), grassland (94%) and remnant peatlands (91%) all show high UA, while built-up (68%), cutover and water (70%) show low UA. The lower UA of the cutover class (70%) can be attributed to the presence of heterogeneous vegetation, resulting in a mosaic landscape following the abandonment of extraction sites. As a result, this class is prone to misclassification, particularly with remnant peatlands (another landscape characterised by heterogeneity) (Fig. 2). The lower UA of water bodies (70%) and misclassification with forestry can be attributed to overlap in spectral signatures in partially vegetated and surface water areas, as shown in Fig. 4.

Discussion

The degradation of Irish-raised bogs due to centuries of human exploitation is widely acknowledged[6,12,13]. Nevertheless, a significant knowledge gap exists in the absence of "robust aerial data" for accurate assessment of land use on the raised bog[14,26]. This gap in spatial data is addressed through the development of the LUCIP taxonomy and its implementation in GEE using Sentinel-2 data. This study provides the first high-resolution wall-to-wall coverage of land use on raised bogs in Ireland. The robust methodology presented here facilitates an accurate assessment of the magnitude and extent of land use and CO_2 emissions on these ecosystems. It utilises cloud computing (GEE), temporal mosaicking, and machine learning (random forest and high-resolution remote sensing imagery (Sentinel-2)) to overcome the issue of persistent cloud cover in Ireland. The accuracy assessment results (overall accuracy of 89%) showed good agreement between the map and the reference data.

Currently, the Irish National Inventory Report (NIR) only considers peat extraction activities (industrial/domestic) in the "managed wetlands" category for all peatlands (blanket and raised bogs). This area is reported as 70,020 ha, of which 400 ha is domestic cutover with the remainder being industrial cutaway, and emissions calculations in the NIR are also reliant on these area estimates[32]. In literature, this figure is ~ 80,000 ha, which is mainly the BnM landholding[12,14,32,60]. However, the findings of our study which focused only on raised bogs, indicate that peat extraction (cutaways and cutovers) is considerably more prevalent than currently reported and extends to approximately 119,000 ha. This is 70% higher than the NIR-reported "managed wetland" area figures for all peatlands. Hence, we address the overall ambiguity in exisiting land use estimates by providing accurate spatially explicit land use information derived from robust remote sensing methods.

The results depict heterogeneous land use in raised bogs across Ireland. The midland raised bogs (Fig. 4a, b, c, and f) are dominated by industrial mining activities as well as conversion to grassland and forestry. The more peripheral raised bog areas to the west, northwest, and southwest of the midlands are dominated by conversion to grassland and forestry. In general, the most extensive land use on raised bogs is agricultural grassland which is distributed across the region. Grasslands mainly occur on the margins of cutaway, cutover and remnant peatlands. The remnant peatland class, which represents the remaining areas of the raised bogs, are not in pristine condition, and are more abundant towards the North and West of the midlands, away from the areas of intensive industrial peat extraction activities. The BnM Peatland Climate Action Scheme (PCAS) aims to restore degraded peatlands within BnM landholding and is a good start for mitigation and adaptation, which are more intact raised bogs in the north and west that could be targeted for active restoration by policymakers, facilitating carbon retention in these ecosystems. It is also pertinent to mention that the PCAS was initiated at some of the former industrial peat extraction sites during the timeframe of this study. Most of these areas are still bare peat which means the data produced in this study could be used as baseline data for tracking and monitoring the PCAS over time.

Class	A	B	C	D	E	F	G	Total	UA (%)
Cutaway (A)	**164**	12	1	8	2	10	0	197	83
Cutover (B)	0	**91**	0	4	15	19	1	130	70
Water (C)	1	0	**35**	8	2	0	4	50	70
Forest (D)	1	2	0	**244**	4	1	0	252	96
Grassland (E)	2	1	1	12	**624**	6	14	660	94
Remnant Peatland/High Bog (F)	1	2	0	2	5	**111**	0	121	91
Built-up (G)	0	0	0	3	13	0	**34**	50	68
Total	169	108	37	281	665	147	53	**1303**	**OA (%)**
PA (%)	97	84	94	86	93	75	64		89.2

Table 6. Result of accuracy assessment for the seven land use classes, including Overall Accuracy (OA), User's Accuracy (UA), and Producer's Accuracy (PA). The emboldened diagonal elements represent accurately classified areas.

Overall, the maps show that the current level of human-induced degradation of these raised bogs through land-use change requires immediate action for sustainable management of these ecosystems.

On BnM landholdings, industrial extraction activities have gradually ceased over the past two decades, with an announcement of complete cessation in 2021. The results of this are beginning to be observed in the data. At the Blackwater site (Co. Offaly) site (Fig. 5), areas are classified as remnant peatlands, which is an indication of revegetation after the cessation of extraction activities (pre-2000) and subsequent rewetting in 1999[61]. These sites are going through a transformation with land use conversion to forestry or a diverse mosaic of vegetation communities composed of heather, shrubs, grasses, and interspersed larger plants. The forestry areas in Fig. 5, are on Coillte landholdings and are highlighted with a grey outline. Other areas with surface water are possibly signs of rewetting activities and are represented by surface water here (Fig. 5). Vegetation cover at Blackwater has increased over the years, albeit slowly, with Sphagnum mosses and other bog species recolonising the area i.e., sparse remnant peatlands patches among the prevalent bare peat (cutaway) (Fig. 5). This recovery process is not only important for carbon sequestration and climate change mitigation but also for the restoration of the unique biodiversity and ecosystem services provided by peatlands. An SAC site is outlined (white dotted line) in the bottom right (Fig. 5) and shows a good example of what is considered a "near natural" raised bog e.g., intact centre but degraded margins where substantial cutting has taken place and areas converted to grassland. These changes can be seen using Sentinel-2 which demonstrates the utility of this methodology for tracking and monitoring land use change in raised bogs over time.

The EU has established a range of regulations and initiatives that directly or indirectly require restoration and sustainable management of peatlands. These include the Habitats Directive (Council Directive 92/43/EEC), Water Framework Directive (Directive 2000/60/EC), EU Biodiversity Strategy for 2030, Common Agricultural Policy (CAP), Natura 2000 Network (Directive 2009/147/EC), LIFE Programme, EU Climate Adaptation Strategy, and more recently the Nature Restoration Law which includes restoration of peatlands by binding targets and net zero CO_2 emissions from these ecosystems by 2050. The effective implementation of these initiatives is only possible through robust mapping, tracking, and monitoring[62] methodologies such as those proposed in this study.

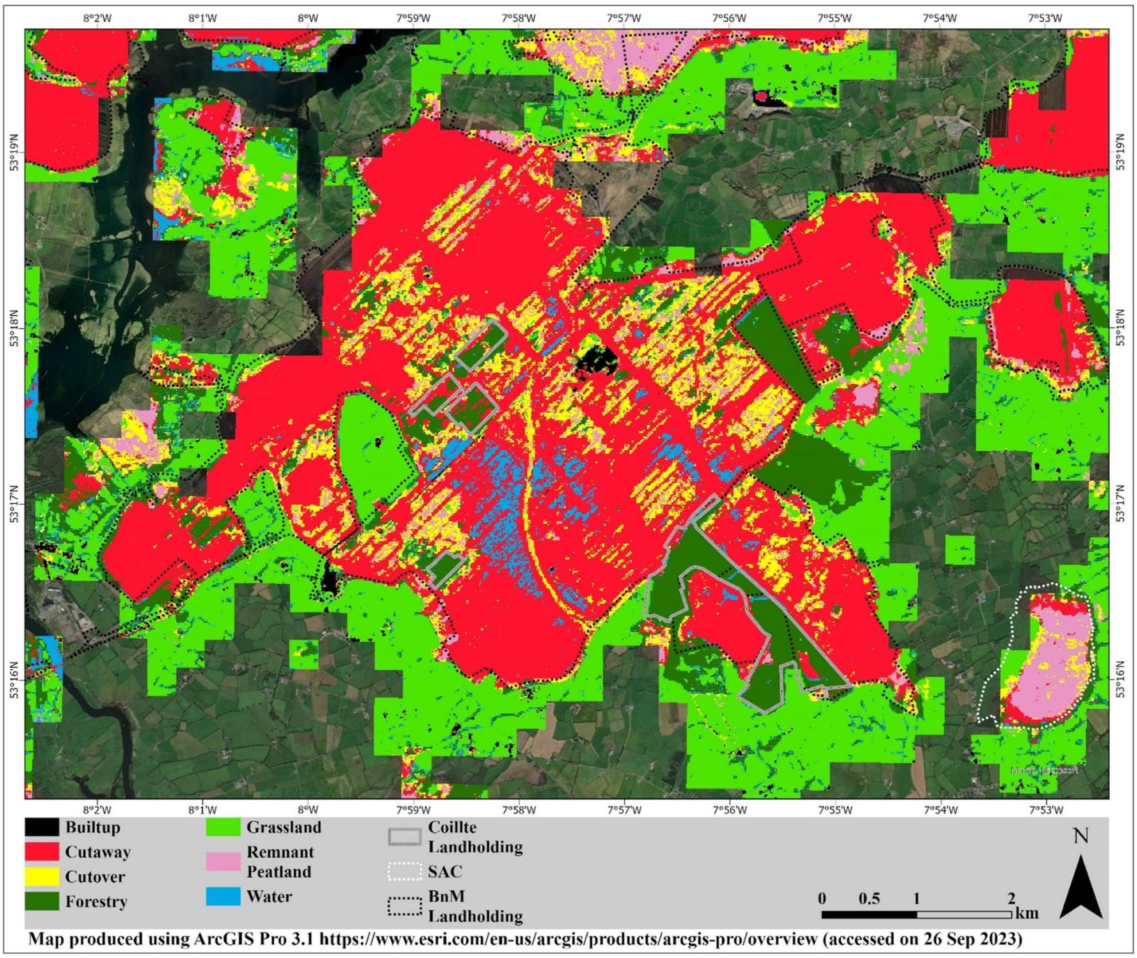

Figure 5. Typical example of a former industrial bog complex mapped in this study. The areas outlined by the black dotted lines are within the BnM (Bord na Móna) landholdings, whereas the white dotted lines in the southeast section of the map show a bog under SAC (Moyclare Bog). The grey boundaries in the BnM landholdings and outside of it are Coillte landholdings.

The map produced here serve as an important indicator for determining the baseline status and condition of these ecosystems as well as providing a quantification of CO_2 emissions hotspots. By providing a detailed map of BnM/non-BnM industrial activities and domestic extraction activities, this study not only highlights these activities in a spatial context but also estimates emissions from them. The emissions calculated in this study based on IPCC T1 and Ireland-specific T2 EF show a substantial difference. The IPCC default emission factor is higher than the Irish T2 EF resulting in higher emission estimation. One of the limitations of using IPCC T1 EFs is that these EF are based on limited case studies with diverse geographical locations, climatic conditions and ecology not necessarily suited to Irish Peatlands. The EFs proposed by Aitova et al.[26] and the EFs from the study by Jovani-Sancho[57] are based on measurements from specific sites in Ireland, the United Kingdom and Germany, and may not be a true representatives of other sites in the country. For example, T1 EFs for grasslands (5.3 t CO_2-C ha^{-1} y^{-1}) are mostly based on study sites from Germany, which are under more intensive management practices compared to Ireland[26,63]. This may lead to a substantial difference when comparing T2 EFs for grasslands in Ireland (1.30 t CO_2-C ha^{-1} y^{-1})[26]. While these EFs could be refined specifically for Ireland, their use by Aitova et al.[26] is a significant improvement compared to the T1 EFs. Finally, the delineation of raised bogs in this study relies on an existing peatland extent map i.e., DIPMv2. Although, DIPMv2 is most current peatland map in Ireland, with an overall accuracy of 88%, it tends to underestimate the presence of peatlands with areas smaller than 7 ha[5]. This study can be expanded to these missing areas if the DIPMv2 is updated in the future.

Nevertheless, this study demonstrates the robustness and utility of remote sensing methods to accurately map the land use on peatlands and to integrate these data with the latest T2 EFs thus refining estimates of CO_2 emissions from different land use on Irish peatlands. The LUCIP implemented in GEE facilitates the development of highly accurate land use maps that can aid the refinement of national-scale T2 reporting in these globally rare ecosystems. These integrated spatial datasets can help inform decision-making for sustainable land management practices and conservation. Furthermore, detailed habitat mapping of the remnant peatland class using a high-resolution dataset and integrated Sentinel-1 and 2 approach could be useful for monitoring active raised bog areas in SAC[42,64]. Future work using the LUCIP could address the large knowledge gap regarding land use type and extent on blanket bogs, which account for ~70% of peatlands in Ireland and have not been studied at this level in Ireland. It is important that the EFs and emissions are assessed for these areas to identify C and GHG emission hotspots and areas for targeted restoration.

Conclusion

In this study, a spatially explicit dataset of land use on Irish raised bogs was created by integrating the DIPMv2 and Sentinel-2 satellite images collected between 2018 and 2020. Overall, the accurate results (OA = 89%) of this study provide valuable insights into the spatial extent of land use in raised bogs in Ireland. These data were integrated with T2 EFs to refine the estimation of CO_2 emissions from the four major land classes on raised bogs. These spatial data on land use can inform policies on land use and emissions at a national scale. The map also enhances the current understanding of the extent and scale of different land uses (especially peat-extraction activities) in a spatial context. The state and condition of raised bogs in Ireland present a pressing concern due to their substantial CO_2 emissions. Urgent measures are required to address this issue, including (i). mitigating emissions and (ii). implementing sustainable management practices to promote carbon sequestration within these ecosystems and prevent additional degradation. This spatial information can be used to inform the development of more sustainable approaches to peatland management in the country, the decision-making process for developing such policies and effective strategies to mitigate these management impacts.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

W.H. lead the preparation, creation and/or presentation of the published work, specifically writing the initial draft. He took a lead role in the development and design of the methodology using Remote Sensing and GIS analysis in both GEE and ArcPro as well as in data curation. Both W.H. and J.C. conceptualised the study. R.I. contributed to the emission calculations. Both M.S. and J.C. contributed to the review and editing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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