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The global extent of biodiversity offset implementation under no net loss policies

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'No net loss' (NNL) biodiversity policies, which seek to neutralize ongoing biodiversity losses caused by economic development activities, are applicable worldwide. Yet, there has been no global assessment concerning practical measures actually implemented under NNL policies. Here, we systematically map the global implementation of biodiversity offsets ('offsets')—a crucial yet controversial NNL practice. We find, first, that offsets occupy an area up to two orders of magnitude larger than previously suggested: 12,983 offset projects extending over $153,679^{+25,013}_{-64,223}$ km^2 across 37 countries. Second, offsets are far from homogeneous in implementation, and emerging economies (particularly in South America) are more dominant in terms of global offsetting area than expected. Third, most offset projects are very small, and the overwhelming majority (99.7%) arise through regulatory requirements rather than prominent project finance safeguards. Our database provides a sampling frame via which future studies could evaluate the efficacy of NNL policies.

No net loss of biodiversity

Halting global biodiversity loss is one of the leading sustainability challenges of the twenty-first century[1]. Impacts associated with economic development (for example, agricultural expansion, infrastructure development, urbanization and resource extraction) are the most significant anthropogenic drivers of biodiversity decline[2,3]. In turn, arresting further declines will in part require the implementation of environmental policy principles designed to reduce biodiversity losses associated with economic development. One such policy principle is 'no net loss' (NNL). Rooted in US and German nature conservation policies in the 1970s, the NNL principle has become widespread, and has now been estimated to be part of public policy for 69 (refs [4,5]) to as many as 108 (https://portals.iucn.org/offsetpolicy/) countries globally. Essentially, NNL requires the detailed quantification of predicted biodiversity losses associated with development projects, and the application of a 'mitigation hierarchy' to those losses. The mitigation hierarchy generally takes the form 'avoid, minimize, remediate, offset', designating the sequentially preferred actions to be applied to meet the ultimate objective of ensuring a neutral net biodiversity outcome[6]. The final stage in the mitigation hierarchy—biodiversity offsetting, whereby residual predicted losses are fully compensated for via the prevention of unrelated losses ('avoided loss') or ecological restoration measures elsewhere[5]—raises a host of practical and ethical concerns, including the moral acceptability of trading in losses and gains of components of biodiversity[7,8]. Nonetheless, NNL policies (and particularly biodiversity offsets) have generated much interest among conservationists and policymakers, in turn becoming the subject of extensive research[9].

Implementation of NNL biodiversity policies. Despite 40 years of policy evolution, there has so far been no comprehensive worldwide assessment of the scale on which conservation activities arising via NNL policies have actually been carried out, nor how they are distributed[4,10]. This lack of evidence means that it is impossible to make generalizations about the impact of NNL policy, or characteristics of NNL implementation. In turn, it remains unclear, for example, to what degree biodiversity loss is prevented during development activities, to what extent compensatory mitigation activities tend to involve ecosystem restoration over the more nuanced practice of avoided loss offsets[5], whether the mitigation hierarchy tends to be implemented in habitats that are feasible targets for restoration activities and, ultimately, how effective mitigation activities have been in striving towards achieving NNL. The bulk of the NNL literature is theoretical, and, to date, analyses of implementation have focused on specific projects (for example, refs [11–13]) or subnational regions (for example, ref. [14]). This lack of information on the extent and nature of global NNL implementation hampers efforts to make clear, empirical statements concerning controversies surrounding NNL, facilitate evidence-based NNL policy development and evaluate the contribution made by NNL to biodiversity conservation. The need to assess the validity of NNL as an approach has become increasingly pressing, with the introduction of far-reaching policies supporting its use[4].

Simultaneously mapping the implementation of all components of the mitigation hierarchy enforced under NNL policies is not currently technically feasible (see ref. [15] on 'avoidance' measures in US NNL policy). However, biodiversity offsets ('offsets') are the most visible and readily identifiable outcome of NNL policies. Therefore, here, we provide a first current and realistic order-of-magnitude estimate for how many biodiversity offsets have been implemented under NNL policy globally and where these are distributed. Our findings are not only of interest in shining light on key descriptive statistics concerning offset implementation. Additionally, our study effectively provides a global sampling frame for use in future empirical studies seeking to evaluate the general effectiveness of NNL. Note that we did not seek to obtain data on the general effectiveness of offset projects (in terms of achieving biodiversity conservation objectives) as part of this study, and doing so would require an entirely different experimental design. We note, however, that understanding the effectiveness of offsetting is a crucial long-term goal for future NNL research.

Results

We found evidence for 12,983 biodiversity offset projects that are currently completed or in the process of implementation, occupying

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at least $153,679^{+25,013}_{-64,223}$ km² worldwide (note the asymmetrical positive and negative uncertainty bounds). For context, the previous best estimates of global offset coverage by area were ~2,000 km² and ~85,000 km² (ref. [16]), and the largest global offset dataset previously constructed contains 70 offset projects[17], although not all offsets included had commenced implementation in any of these cases. The offset projects in our database (Supplementary Data 1) range in size from those that occupy a negligible area to one that occupies some 50,000 km² (associated with the Oyu Tolgoi mine in Mongolia—an areal figure that is open to substantial interpretation). It is of note that the three largest single offset projects in the database—the aforementioned offset for Oyu Tolgoi, Uatumã Biological Reserve in Brazil (compensating for the Balbina hydropower plant) and Saigachy reserve in Uzbekistan (compensating for multiple extractive sector activities)—together constitute ~43% of the total areal estimate in the database (Supplementary Data 1). Although these large projects represent a substantial proportion of the areal estimate, the median area occupied by offsets is 0.021 km², and the overwhelming majority (92.9%) of offset projects are small (that is, they occupy an area <1 km²).

Geographical distribution. Geographically, offset projects can be found on every major continent except Antarctica (Fig. 1a and Table 1). The majority of biodiversity offset research by output has largely been carried out by academics based in North America, Western Europe and Australasia[9] and, perhaps unsurprisingly, these regions also feature high numbers of offset projects (Australia, n = 395; Canada, n = 473; Western Europe, n = 1,824; USA, n = 1,729; Fig. 2 and Table 1). However, even though the data obtained are less detailed and reliable (according to our definitions of these terms; see Methods), even higher numbers of offset projects have been recorded in Brazil (n = 2,514) and Mexico (n = 5,970). Indeed, the region containing the greatest proportion of offsets by area is Central and South America (69,508 km², or ~45% of the total estimated; see Fig. 2). Despite the publication of specific articles relating to key countries in Central and South America for offset activity—notably Brazil[18], Colombia[19] and Mexico[20]—the region has proportionally received less intensive research attention than elsewhere[9,21]. Combined with the recorded offset activity in Africa (13,684 km²) and Asia (64,127 km², a figure that incorporates the aforementioned Oyu Tolgoi project offset), the bulk of offset activities both numerically and by area are located in less industrialized and emerging economies (Fig. 2).

We obtained point locations for 3,416 of the offsets in the database (Supplementary Data 1), providing the opportunity to map offset implementation on a finer (that is, subnational) spatial scale for some regions (the Americas, Australasia, Europe and sub-Saharan Africa; Fig. 1b). Point location data could not be found for Brazil, China or Mexico despite extensive documented offsetting activity (Table 1). We found no evidence for any NNL policies leading to offsets being implemented in the high seas, despite marine NNL policies existing[22] and being included within our scope—hence, the apparent focus of the database on terrestrial and coastal regions.

Biodiversity offset characteristics. *Driver for implementing offsets.* By far the most common driver for implementing offset projects numerically is public environmental policy (99.7% of all projects), with the remainder driven by requirements from lending institutions that co-finance development projects (~0.15%) or by voluntary corporate commitments (also ~0.15%). However, those implemented in response to lender requirements and corporate commitments tend to be much larger (Fig. 3) and so occupy a disproportionately large area (72,651 km² compared with 81,028 km² occupied by offsets driven by public policy). Indeed, offsets can effectively be divided into two entirely different classes: those driven by public policy (which are numerous and tend to be relatively small) and those driven by lender or corporate requirements (which are rare, but tend to be extremely large; Fig. 3). Of particular interest is the fact that, worldwide, only eight projects have so far commenced implementation as a direct requirement from the International Finance Corporation under their Performance Standard 6 (PS6)[23], despite the fact that PS6 is highly influential and widely considered best practice[24].

Biodiversity offset activities. Biodiversity offsets are typically considered to seek to achieve NNL either through active ecosystem restoration or the prevention of anticipated biodiversity losses ('avoided loss' offsets), both of which result in biodiversity gains depending on the reference scenario[5]. We find that, overall, 19.9% of offset projects implement avoided loss measures, 18.8% implement ecological restoration and another 46.4% seek some combination of the two approaches (leaving 7.3% of offsets that take 'other' approaches and 7.7% unknown).

The approach taken in terms of offset activities varies dramatically by country. For Australia and Sweden, avoided loss offsets constitute <10% of known offsets, whereas they constitute 69% of offsets in South Africa, and probably a higher proportion in Australia when accounting for unknowns (see ref. [25]). 'Other' activities (for example, financial offsets) are much less widely observed (Table 1). Regarding large-scale regional spatial trends, the majority of offsets in North America, Europe and China implement ecological restoration activities, whereas avoided loss activities represent a greater proportion of offsets in the Southern Hemisphere (Australasia and sub-Saharan Africa).

Habitat types. The majority of offset projects are implemented in forests (66.7%) or wetlands (17.5%), although the enormous projects in the steppe and semi-arid habitats of Mongolia (associated with Oyu Tolgoi) and Uzbekistan (the Saigachy reserve) are notable exceptions (Table 1). We did not anticipate the widespread implementation of offsets in forests relative to wetlands and grasslands. This may have been because wetland and grassland offsets tend to constitute a large proportion of activity in more heavily industrialized regions (Australia, Europe and North America; Table 1), which are the source of much of the published academic literature on offsets[9].

Regarding the subset of offset projects for which point locations are available (n = 3,416), we also considered the larger-scale landscape context within which offsets were implemented. To do so, we assessed known offset locations against the 827 terrestrial ecoregions defined by the World Wildlife Fund. The relevant shapefiles were obtained through The Nature Conservancy's spatial data repository (http://maps.tnc.org/gis_data.html) and offset point locations overlaid on eco-region polygons in the open-access software Quantum GIS. The analysis confirmed that offsets have been implemented across the full range of terrestrial ecoregions, but with the majority (92%) being located in boreal, Mediterranean, temperate and tropical forest biomes (7% are found in grassland biomes, including flooded grasslands). Note, again, that this represents a subset of the offset projects in the database.

Discussion

Significance and policy relevance. None of the global offset studies cited[16,17] claims to be a comprehensive evaluation, so they would be expected to underestimate offset implementation, even though they were not limited strictly to biodiversity offsets in the process of implementation. Nonetheless, we did not anticipate the magnitude of our findings (over 10,000 projects occupying an area of over 100,000 km²—an important outcome in itself). The implication is that, despite hundreds of journal articles on the topic[9], the global offset portfolio has grown more quickly and is far more widespread than could previously have been realized. By way of comparison, the

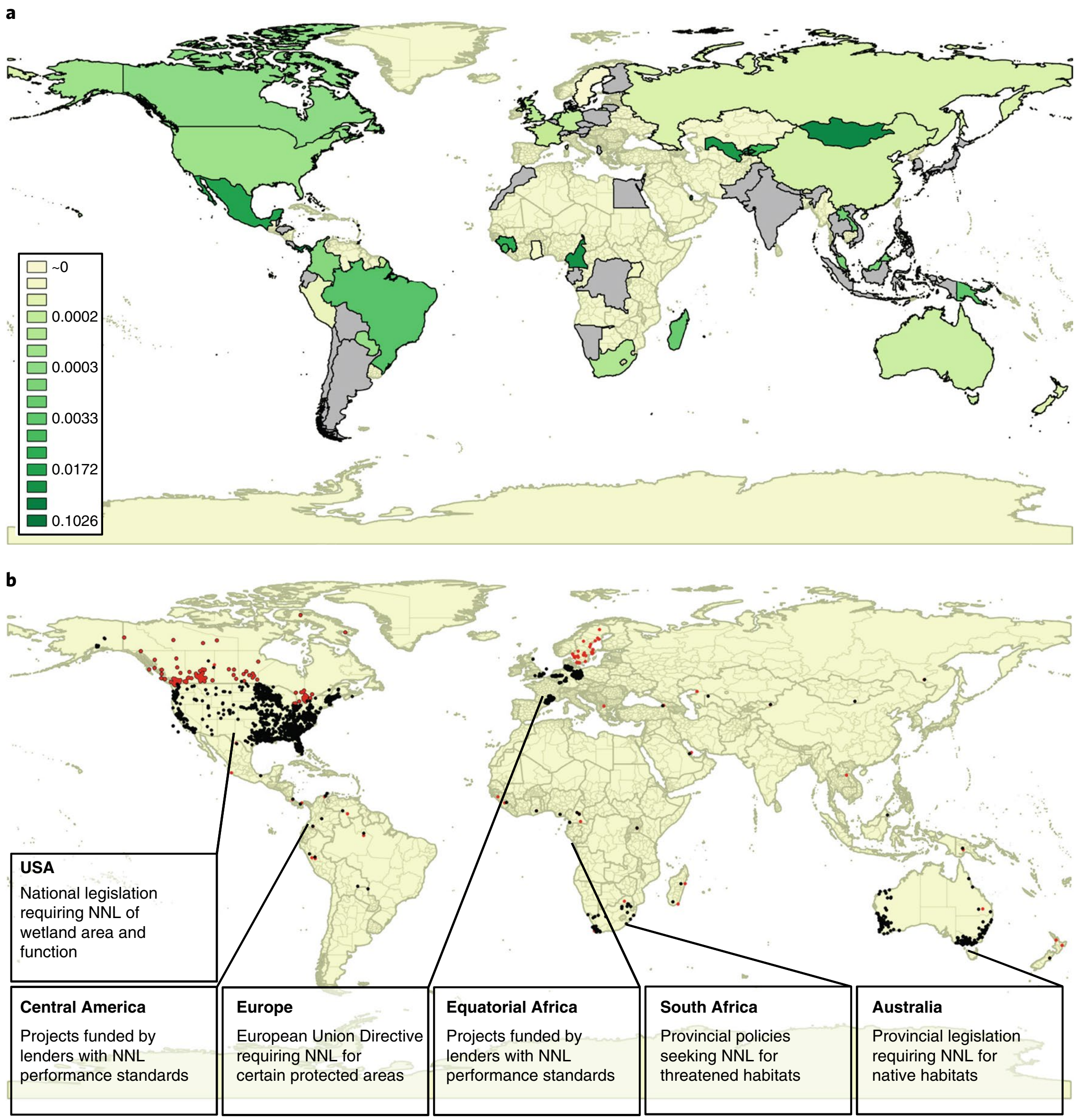

Fig. 1 | Spatial information from the biodiversity offset database. a, Green shading shows the ratio of the area occupied by biodiversity offsets in each country to the total area of that country ($n=12,983$ offset projects in 37 countries). Grey shading shows the countries with relevant policies, but where no evidence of offset implementation was found ($n=37$). **b**, Locations of all documented biodiversity offset locations ($n=3,416$; black dots) and known associated development projects ($n=247$; red dots). Inset, brief descriptions of the main drivers for the offset projects in selected regions. Created on QGIS Geographic Information System version 2.8.1; base data from Natural Earth version 3.1.0.

offset portfolio captured by our database is currently ~1% the size of the global terrestrial protected area network[26], although the first offset policies were only developed in the 1970s[4]. We note that the conservation outcomes of offsets, and their contribution towards an NNL objective, cannot be determined based on the area they occupy alone. However, this rapid and spatially diffuse growth of the offset portfolio suggests a degree of urgency in terms of evaluating whether and when offsetting can prove effective in supporting achieving NNL, and that offset outcomes are more closely and transparently monitored.

Furthermore, we demonstrate that there is substantial variation in the density, extent and type of offset project by geographical location and policy driver. Biodiversity offset projects are far from homogeneous in implementation. In turn, this suggests that offsets may be better grouped for analysis of effectiveness by their characteristic traits (for example, associated policy driver and policy specifications) than by their geography, if at all. In fact, the degree of heterogeneity in implementation suggests that it is questionable whether generalizations about findings on offset performance should be made at all. Importantly, our finding that certain regions (particularly South America) are more dominant in terms of global offsetting activity than might have been expected could shift research priorities. To even begin to understand the conservation outcomes of offsetting, increased research focus will need to be on the bulk of the extant offset portfolio by extent (South America, Africa and Asia) rather than where it currently rests (North America, Europe and Australia[9]).

To a first approximation, all offset projects have so far arisen through regulatory requirements. Examination of our database (Supplementary Data 1; see also Fig. 1 and Table 1) suggests that regulatory NNL-type policies result in networks of small offset sites, probably with limited landscape-scale coordination. An important

Table 1 | Country summaries from the biodiversity offset database

Country	Number of biodiversity offsets	Area of biodiversity offsets (km²)[a]	Management activity (%)					Habitat type (%)				
			Av. L.	Rest.	Both[b]	Other	Unknown	Forest	Grassland	Wetland	Other	Unknown
Australia	395	805 ± 344	8	11	6	12	63	34	25	6	7	28
Brazil	2,514	32,400 ± 23,019	100	0	0	0	0	100	0	0	0	0
Cameroon	4	9,120 ± 7,093	100	0	0	0	0	100	0	0	0	0
Canada	473	2,939 ± 2,086	0	99	1	0	0	1	0	99	0	0
China	ND	804 ± 804	0	100	0	0	0	100	0	0	0	0
Colombia	4	1,060 ± 511	25	0	75	0	0	100	0	0	0	0
Costa Rica	2	ND	0	0	100	0	0	0	0	0	100	0
France	975	28.4 ± 0.3	0	0	0	87	13	0	0	0	0	100
Georgia	1	0.1 ± 0.01	0	100	0	0	0	100	0	0	0	0
Germany	478	53 ± 30	0	14	0	11	76	1	21	15	53	10
Ghana	1	2.5 ± 0.8	0	0	100	0	0	100	0	0	0	0
Guinea	1	2,909 ± 2,909	100	0	0	0	0	0	0	0	100	0
Kazakhstan	1	ND	0	100	0	0	0	0	0	0	100	0
Kyrgyzstan	1	1341 ± 1341	100	0	0	0	0	0	0	0	100	0
Laos	1	280 ± 280	0	0	100	0	0	0	0	0	100	0
Macedonia	3	ND	0	0	100	0	0	0	0	0	100	0
Madagascar	9	1,050 ± 521	0	0	100	0	0	100	0	0	0	0
Malaysia	1	340 ± 340	0	0	100	0	0	100	0	0	0	0
Mexico	5,970	$33,404^{+337}_{-32,002}$	0	25	75	0	0	50	0	0	50	0
Mongolia	1	$50,000^{+5,000}_{-50,000}$	0	0	100	0	0	0	0	0	100	0
Netherlands	116	8.5 ± 3.0	0	100	0	0	0	0	0	0	0	100
New Zealand	4	15.3 ± 2.5	50	0	50	0	0	75	0	0	25	0
Panama	1	2,479 ± 1,215	100	0	0	0	0	100	0	0	0	0
Papua New Guinea	1	1,500 ± 150	100	0	0	0	0	0	0	0	100	0
Paraguay	2	115 ± 90	0	50	0	50	0	100	0	0	0	0
Peru	2	50 ± 45	0	100	0	0	0	100	0	0	0	0
Qatar	1	1,189 ± 1,189	100	0	0	0	0	0	0	0	100	0
Russia	1	1,320 ± 132	100	0	0	0	0	0	0	100	0	0
Sierra Leone	2	304 ± 76	0	0	100	0	0	100	0	0	0	0
South Africa	32	294 + 56	69	16	3	6	6	0	0	0	3	97
Spain	200	ND	0	0	0	0	100	0	0	0	0	100
Sweden	44	0.6 ± 0.4	9	66	0	20	5	0	0	0	0	100
Uganda	1	4 ± 0.4	0	0	0	100	0	0	0	0	100	0
UK	11	0.53 ± 0.12	0	9	0	0	91	9	0	0	0	91
USA	1,729	2,457 ± 860	0	100	0	0	0	0	0	100	0	0
Uzbekistan	1	7,352 ± 735	0	0	100	0	0	0	0	0	100	0
Venezuela	1	ND	0	0	100	0	0	0	0	0	100	0

[a]Uncertainty was estimated on the basis of our uncertainty protocol (see Methods). [b]Combination of Av. L. and Rest. Av. L., avoided loss offsets; Rest., restoration offsets; ND, no data.

implication is that offset activity may primarily translate into a network that does not necessarily have substantial landscape conservation value. Equally, where these sites are privately owned, considerable existing biodiversity values could be being locked up in an uncoordinated network of mini 'private protected areas', which could in turn complicate both monitoring of biodiversity trends and public access to biodiversity value (see ref. [27]). This deserves further research attention (see the section 'Further uses').

Our database suggests that financial lender safeguards (including, but not limited to, International Finance Corporation PS6) and voluntary corporate commitments (see ref. [28]) have not yet led to the implementation of many offset projects on the ground ($n = 22$ and $n = 20$ projects, respectively). Yet, given examples in our database—such as projects in Madagascar, Mongolia and Uzbekistan—developers will apparently countenance rather enormous and ambitious conservation interventions if project finance requirements specify a need to seek NNL. These insights potentially provide arguments both for and against any contention that non-regulatory NNL policies are viable routes towards implementing large-scale nature conservation measures.

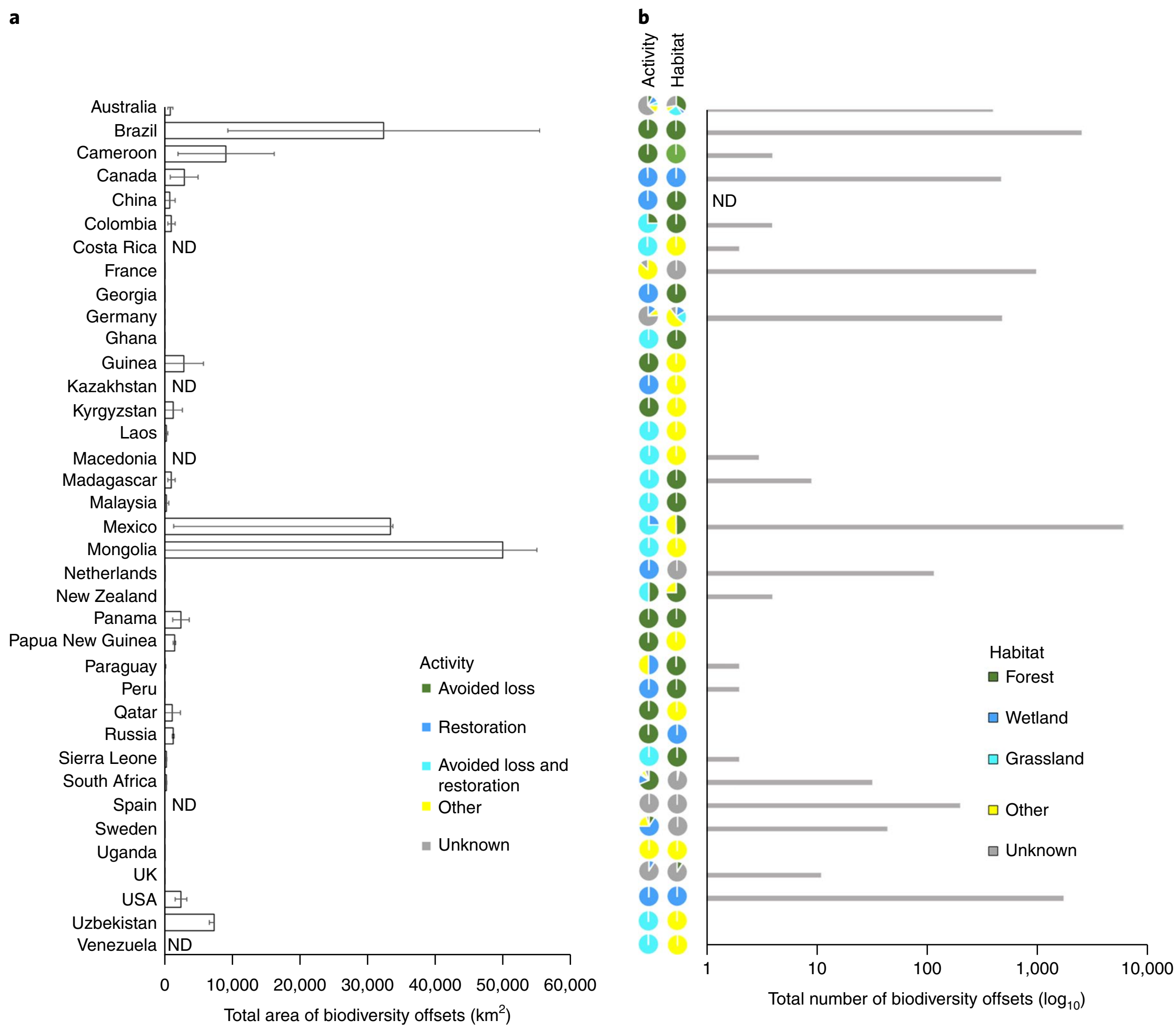

Fig. 2 | Key characteristics of biodiversity offsets extracted from the database. a,**b**, For all countries with some record of implementation, the area (**a**) and number (**b**) of biodiversity offsets is given. Uncertainty in **a** was estimated on the basis of our uncertainty protocol (see Methods) and is shown by error bars. Pie charts show, by country, the main conservation management activity and habitat type associated with offsets, for which the proportion is based on the total number of offsets in that country. ND, no data.

Data limitations. The global offset data presented here range widely in quality—from those obtained via detailed, comprehensive and reliable government registers (for example, Australia) to those inconsistently regionally collated via reliable and detailed registers (for example, Germany) and incomplete headline figures in the grey literature (for example, China). Consequently, an important component of our results is the estimates of uncertainty bounds in the areas occupied by offset projects, via the application of a systematic protocol (see Methods). Although necessarily estimated, these bounds illustrate the degree of uncertainty in our overall estimates of the areas occupied by offsets. In turn, we note that our database represents an order of magnitude estimate of existing implementation.

A key limitation to the construction of the database is that our search was carried out primarily in English (see Methods). We give some qualitative indication of the effect of this limitation by continent. (1) in North America, English is the primary regional language, and most information on offset projects is likely to be available in English. Consequently, searching in English is unlikely to constitute a limitation here. (2) In South America, offsets implemented as a result of lender requirements (for example, the Inter-American Development Bank) are typically accompanied by English language documentation. Offsets implemented in response to national regulation are less straightforward. While for key countries (for example, Brazil and Mexico), some information is available in the English language literature, these countries remain a key gap for the authors in terms of fully understanding implementation. (3) European offset data were sourced via collaboration with non-English language speakers (Dutch, French, Spanish and German) on a previous project[10]. Data collected for Sweden were contrasted with a comparable national study published in English[29], confirming that these findings were on a reasonable order of magnitude. UK data are available in English. A previous study suggested that most offsetting activity in Europe would be captured via these languages alone[30]. We are consequently confident that European offset implementation is captured as far as is currently feasible. (4) Sources of offset-related policy development in Africa (ref. [4] and https://testportals.iucn.org/offsetpolicy/) suggest that most offsets currently implemented (with the exception of South Africa) result via lender or corporate requirements. For such projects, project documentation is generally available in English. The public biodiversity offset register sourced for South Africa is in English. We are thus confident that searching in English does not represent a substantial limitation for African offsets. (5) For Asia, after searching using keywords in English,

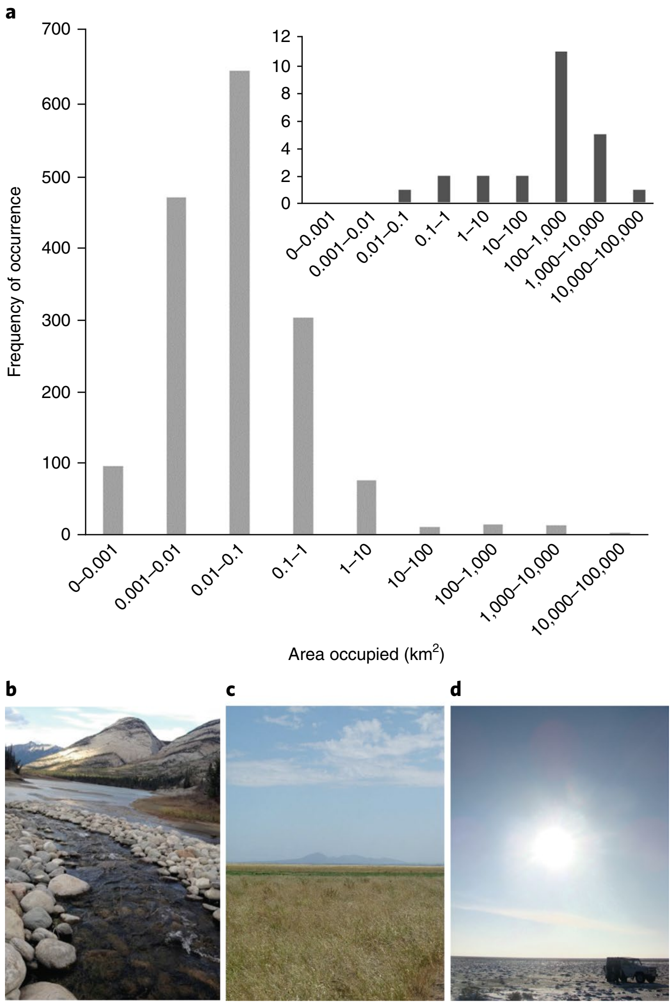

Fig. 3 | Frequency distribution of offsets by area, with examples from various countries. a, Frequency distribution of all biodiversity offsets in the database associated with areal information, by area occupied. Inset, equivalent frequency distribution for the subset of offsets driven by either project finance requirements or voluntary corporate commitments. The mean areas occupied by offsets for projects driven by public policy versus those driven by lender and corporate requirements are substantially different (48.5 and 3,100.4 km^2, respectively). **b–d**, Examples of 0.001–0.01 area offset (fish habitat restoration offset in Canada; **b**), 0.1–1 area offset (grassland restoration offset in Australia; **c**) and 1000–10000 area offset (mammal conservation ('avoided loss') offset in Uzbekistan; **d**). Photo credit: J. W. Bull.

the authors were able to utilize Russian language skills to interpret information on offsets in Russia and the former Soviet states (for example, Kazakhstan and Uzbekistan). Extensive English language literature is available for the major offset project in Mongolia (Table 1). Conversely, China and Southeast Asia were problematic regions in linguistic terms, and data were relatively inaccessible. (6) English is the primary language within Australasia, so again searching in English was unlikely to constitute a limitation. In summary, while our regional findings should absolutely be viewed in light of linguistic limitations, we do not consider them to invalidate the overall conclusions.

Our approach to consulting experts on the completeness and validity of the data we had obtained was to use a process of chain referral (see Methods). While such an approach is effective from the perspective of identifying key individuals and eliciting understanding from them, it is less systematic than seeking a random and institutionally representative sample of experts[31]. Furthermore, using chain referral could feasibly have introduced biases to our data collection (for example, if our extended network of offset researchers had no connection to parallel networks in different geographical regions or disciplinary fields). In turn, where we classify certain datasets as not being detailed or reliable, this could reflect our methodology, as well as the data themselves. However, developing a truly random sample of experts for consultation—stratified by, for example, geographical region or driver for offsets—was not feasible for this study, due to the lack of any global sampling frame for offset activity or NNL implementation more generally. Therefore, we considered chain referral the best available approach.

Certain data presented here suffer from problems with accessibility. Some data licenses in Germany, for example, prevent the replication of the data themselves elsewhere (although the data are publically available and we can present the results of analyses). A proportion of the data from Australia are not available publically, and were provided in relation to our study under agreement that the raw data themselves would not be shared. Finally, data on offset projects associated with financial lenders and businesses are not systematically stored online, and an overview was obtained by speaking with expert contacts within the organizations themselves. These are known challenges to the evaluation of NNL implementation[10], and highlight the importance of the progress made in the present study. We considered problems with accessibility when developing our uncertainty protocol (for example, uncertainties concerning the degree of completeness in the data, and uncertainty about whether offset implementation has been overestimated or falsely claimed by responsible parties). Consequently, we have attempted to account for these potential sources of uncertainty in reporting our overall findings (see Methods).

Further uses. Despite the limitations discussed, our database constitutes a global sampling frame for use in inferential offset research, and a foundation on which a database for NNL interventions more broadly could eventually be constructed. It is imperative that an empirical assessment of NNL implementation be carried out, to enable the development of genuinely evidence-based policy. The information contained in our database does not provide a basis for judging the performance of NNL policies. However, the goal of this study was never to judge the performance of NNL policy, as we have made explicit. Rather, our focus here was to understand the extent to which NNL policies have resulted in conservation activity on the ground (that is, implementation). The present study into NNL implementation builds on previous studies into global NNL policy development[4], and is a crucial intermediate step towards eventually evaluating the performance of NNL policies. This would require on-the-ground assessment of all our samples of the individual projects reported in this database.

Our database already informs previously key unknowns in offsetting (global extent, typical characteristics, dominant offset management activities and habitats commonly affected), but could be expanded to explore other important considerations. For instance, the need for offsets to represent 'like-for-like' gains where possible[32], or for spatial proximity between developments and associated offsets[33]. Issues like these, concerning whether to permit flexibility in offsetting[34], could be explored by interrogating our database and expanding it to include information on associated development projects. Such information is currently a relatively small component of the data collated (Fig. 1b and Supplementary Data 1). An equally important extension would be to establish which actors become the ultimate owner of offset projects. If offsets represent an increasingly substantial approach to nature conservation, and offsets are predominantly implemented on private land, policymakers should be concerned about a transfer of biodiversity value into private ownership. While not necessarily a problem in terms of the maintenance of biodiversity, such an outcome might hinder public access to nature and the provision of cultural ecosystem services[35].

Beyond questions regarding biodiversity offsets, our database provides a basis for exploring NNL policy implementation more broadly. To date, much of the literature on NNL policy has focused on offsetting, with relatively little on the other components of the mitigation hierarchy (for example, avoidance measures). Yet, impact avoidance might be considered the key objective for NNL by conservation stakeholders[12,13,15]. To explore this in detail, our database would have to incorporate newly generated data on the avoidance, minimization and remediation measures preceding each biodiversity offset in association with the relevant development(s). This endeavour would require substantial investment and resources and, since primary data collection would be necessary, it would not be technically possible on the basis of the approach we have taken here. However, undertaking such an assessment is the only way we will ever be able to truly assess to what degree NNL policy could be resulting in negative, neutral or even positive outcomes for nature.

Methods

Drivers for biodiversity offsets. We carried out a form of systematic mapping exercise. These are exercises that "do not aim to answer a specific question, but instead collate, describe and map findings in terms of distribution and abundance of evidence"[36]. It was not appropriate to develop a sampling strategy, as we were concerned with carrying out a census of biodiversity offset projects globally. We defined the scope of the census guided by the starting assumption (see ref. [4]) that NNL is primarily enabled through three drivers: (1) government policies; (2) project finance performance requirements; and (3) internal corporate policies. Accordingly, our census incorporated offsets implemented (1) within the relevant countries ($n=69$; ref. [4]), (2) via projects financed by the relevant development banks or members of the Equator Group ($n=6$ and $n=92$, respectively[37]) and (3) companies with known NNL-type corporate policies ($n=32$; ref. [28]). Note that, according to the newly developed Global Inventory on Biodiversity Offset Policies database (https://testportals.iucn.org/offsetpolicy/), the number of countries that have a policy in place that enables biodiversity offsets (stages 2 and 3, according to the Global Inventory on Biodiversity Offset Policies definition) could be as high as 108. However, since this database remains a test portal and has not been peer-reviewed, we use the value stated by Maron et al.[4]

Definitions. We excluded any so-called offset projects that were not associated, either explicitly or implicitly, with an NNL objective; that is, they: (1) provide additional substitution or replacement for unavoidable negative impacts of human activity on biodiversity; (2) involve measurable, comparable biodiversity losses and gains; and (3) demonstrably achieve, as a minimum, NNL of biodiversity[8]. For the avoidance of doubt:

- We included all offsets that arise from policies with a specific NNL objective and attempt to evaluate full and quantifiable compensation for development impacts (for example US wetland banking);
- We included offsets for which the goal is to fully and quantifiably compensate for development impacts, even if an NNL objective is not stated in so many words as an implicit NNL objective (for example, the UK pilot biodiversity offset policy). This recognizes that, in some instances, offsets can arise in the absence of a clearly stated NNL goal;
- We did not include any offsets implemented under a policy that has no requirement for full and quantifiable compensation for development impacts (even if an NNL objective is claimed). This recognizes that even if a policy has an explicit goal of NNL, this might not be demonstrable in any way.

Regarding the degree of 'implementation', we included all offsets that have reportedly been implemented (see 'data collection'), or had at least commenced physical implementation. We excluded any offsets that had been designed but for which delivery had not commenced. For information, a list of projects that we excluded from inclusion in the database on the above grounds is included in the Supplementary Notes.

Due to international variation in terminology, we also clarify what we consider an 'offset project'. In some instances, a single restoration project offsets a single development. In others, multiple restoration projects combine to compensate for a single development. Alternatively, 'habitat banks' (a collection of previously implemented offset actions from which developers can buy credits) are aggregated offsets, but potentially associated with multiple development projects. For consistency, we considered a single 'offset project' to be a contiguous area within which ecological compensation activities are undertaken through NNL-type policy. Consequently, we treated habitat banks as single offset projects. We also note that nature conservation outcomes of biodiversity offsets cannot generally be determined based on the area they occupy alone, for which one must also consider the condition of the relevant habitat before and after the offset and any associated multipliers[33]. However, we consider data on the number and area of offsets useful proxies for assessing global offset activity, if not outcomes.

Data collection. To systematically compile all relevant and available data on offset projects in the process of implementation, we began with the set of policy drivers outlined in the section 'Drivers for biodiversity offsets'. Thus, we implemented the search in turn: (1) for each relevant subnational region, each country and each multinational region; (2) for each financial lender; and (3) for each corporation from the sources mentioned. The search encompassed the academic literature, grey literature, project and policy documentation, and any relevant public or private sector online portals. To perform the mapping exercise, we employed both the Google and Google Scholar online search engines with fuzzy search terms. The decision to use fuzzy search terms was taken as a result of considering the known linguistic vagueness often associated with NNL projects[38], and because the research goal was to compile as comprehensive a dataset as possible. The fuzzy search terms 'biodiversity offset', 'biodiversity compensation', 'compensatory mitigation', 'no net loss', 'net gain' and 'net positive impact' were used, in combination with the relevant driver (for example, 'Australia', 'Rio Tinto' and so on). That is, we combined each of the 6 fuzzy search terms with: (1) each of the 69 countries; followed by (2) each of the 98 lenders implementing safeguards ($n=6$) or belonging to the Equator Group ($n=92$); followed by (3) each of the 32 corporations with stated NNL-type commitments. This meant that 1,194 separate searches were completed in total using each search engine. Since each individual search consequently returned a very large number of hits, we considered each individual hit in order of return until either (1) no further relevant data were found or (2) we reached the tenth page of the results (whichever came second).

Expert chain referral. To complement the data review process and provide a degree of independent validation[36], and in recognition of the likelihood that many data would evade such a search (see 'Data limitations'), we then carried out an entirely separate process of expert chain referral. We contacted a network of established NNL experts, where 'experts' were considered to be those either publishing academic research on offsets in that country in peer-reviewed journals, or those working directly on offset projects (Supplementary Table 1). These individuals were asked to indicate all known data sources on offset implementation for the countries they operated in. Then, we requested that the expert notify us of any other potentially useful individual or institutional contacts. Those further contacts were approached, and so on until we received confirmation that no further data were accessible.

In a limited number of instances, we were informed that certain raw data on offset implementation were under certain license conditions and could not be shared. In such cases, we agreed the conditions in exchange for the data so long as the conditions enabled us to publish analyses on the data (if not the data themselves). Findings based on these data are included in the database. Whenever we were informed that additional offsets had been implemented, but either (1) no documentation was available to confirm the fact or (2) analyses based on the data could not be published, we excluded the data from our database (Supplementary Notes).

Information collated. We collated area occupied, location and any associated information on offset projects that were documented as having been implemented or were in progress, again ignoring offset projects at the proposal or design stage. When offset point locations were described qualitatively in a register or displayed visually online, we extracted approximate latitude and longitude coordinates using the 'Google Maps' online mapping software. Doing so introduced some spatial uncertainty to offset locations, which we estimate to be in the region of ±10 km and consider acceptable for the purposes of assessing broad global distribution and data transparency. Where point locations were not available, locations were recorded in terms of the number of offsets per region or country. We logged all data sources.

Finally, we collected information on: (1) management activities associated with implemented offsets ('offset activities'); and (2) habitats targeted by offsets. The reasons are:

(1) A commonly cited concern in the literature relates to offsets compensating losses through the avoidance of anticipated future impacts ('avoided loss' offsets), without resulting in conservation gains against a fixed baseline. This is in contrast with restoration-based offsets (for example, refs [39,40], but see ref. [41] on counterfactuals). It has also been suggested that avoided loss offsets could pave the way for perverse outcomes such as overestimation of offset gains[25]. In building the dataset, we therefore recorded whether offsets involved 'avoided loss', 'restoration' or alternatives as the primary offset activity;

(2) The habitat in which offsets are implemented is crucial. For instance, habitats with longer restoration times create time lags before conservation gains are realized, which is undesirable in seeking NNL[8]. Furthermore, some habitats are difficult or impossible to restore[39]. Thus, concerns remain that offsetting is inappropriately applied in practice to certain habitats; for example, old growth[40]. We therefore captured information on specific habitat types,

subsequently grouping these into key categories (for example, wetland and grassland).

Data were coded directly into a single master database in Excel format (Supplementary Data 1).

Uncertainty protocol. The uncertainty protocol proposed and described here applies to the overall area occupied by offsets, and was applied to each entry in the database. Offset area is a key metric we report following the compilation of the database on implemented offsets, and the uncertainties in this value are a crucial component of our findings. This protocol follows International Organization for Standardization guidelines on uncertainty of measurement[42] and so describes the measurement of the data quality, sources of uncertainty and decision process for determining combined uncertainties. We treat the uncertainty estimate as the range of values within which the true value is likely to lie (that is, the uncertainty bound is effectively an unquantified confidence interval). Note, though, that the uncertainty bounds have not been calculated based on inferential statistics. To do so would lend undue credence to the quality and accuracy of the data. Rather, the uncertainty bounds are based on informed estimates concerning the accuracy of the information contributing to our database, in turn creating the need for a transparent and systematic uncertainty protocol.

A starting assumption we make is that the maximum uncertainty possible in the reported biodiversity offset area for any one country or policy driver is 100% of the value stated, such that the confidence interval runs between coverage factors ×0 and ×2 of the value stated. We set this maximum value for three reasons. First, it is consequently possible in cases of high uncertainty that the true value for actual implementation is equal to zero, reflecting our aspiration to present a 'conservative' estimate of offset activity. Second, in almost all cases, additional offsets may have been implemented (for which no clear record exists, and of which we were consequently unaware) and, within reason, we wished to reflect this in the uncertainty bounds. Third, we took the decision not to speculate, in any case, that the true offset area might be more than double the area for which direct evidence was found. All three reasons are in keeping with our requirement to have 'conservative' estimates of total headline figures for offset area.

Unless specified otherwise, we assume our uncertainty bounds to be symmetrical around the stated value. Since 'area' is not reported for all biodiversity offsets in our database, our figure for total offset area is probably an underestimate. By not incorporating this as a potential bias in our uncertainty estimates (that is, through the use of asymmetrical uncertainty bounds), we again seek to ensure that our overall estimates are 'conservative' (that is, if at all inaccurate, they are probably lower than the true value). The only cases in which an asymmetrical bound is used are those in which an overwhelmingly large 'interpretative uncertainty' needs to be reported (see 'Sources of uncertainty') and this is explained on a case-by-case basis. Finally, note that for any country that has a policy that drives biodiversity offsetting, but for which no data were found, we assumed (again 'conservatively') that zero offsets had been implemented in that country. We presume that any offsets that have, in reality, been implemented in such countries are likely to be insignificant in terms of the total offset area globally.

Data quality. We begin with an assessment of data quality, based on the sources consulted. This assessment was structured around three categories, capturing whether the data could be considered (1) detailed, (2) complete and (3) reliable. For offset data to be considered 'detailed', we required that, as a minimum, for each individual biodiversity offset project, we were able to obtain at least one distinguishing feature (for example, specific management activity, spatial extent, point location, habitat impacted, and so on). The type of distinguishing feature could vary between datasets (reflecting heterogeneity in disparate global datasets).

For offset data to be considered 'complete', we required that, for the policy driver in question, the data were presented as an exhaustive list for the relevant driver. This would include official government offset registers, or data pertaining to one-off projects required by lender safeguards. Finally, for offset data to be considered 'reliable', we required that the documentation containing the data was either: official government documentation, produced as part of a legislative process (for example, an Environmental Impact Assessment and associated offset strategy), subject to accredited third-party verification (for example, offsets implemented as part of certain development bank finance requirements) or peer-reviewed academic literature.

Sources of uncertainty. Regan et al.[43] divide uncertainty sources into those that are epistemic (knowledge of the state of a system) and linguistic (vagueness, context dependence, ambiguity, indeterminacy of theoretical terms and under-specificity) categories. Informed by Regan et al., we categorized key sources of uncertainty in relation to the following questions:

(1) Have we captured all offset projects, and have we captured them in detail? (epistemic)
(2) Are the offsets we have captured overestimated or falsely claimed? (linguistic)
(3) Are there different possible interpretations for the area occupied by the offsets we have captured? (linguistic)
(4) How accurate is the numerical information we have on those offsets? (epistemic)

Together, these four questions formed the basis of a decision process (see below and Supplementary Fig. 1) for estimating overall uncertainty in the total biodiversity offset area for each policy driver.

Under question 1, we referred to the categorization of offset data as 'detailed' and 'complete' (see the section 'Data quality'). Whenever offset data were not considered 'complete', we assumed uncertainty to be very large (that is, the maximum possible under our protocol). For data that were complete, different pathways were then followed under the protocol for whether the data were 'detailed' or not, in relation to question 2.

Under question 2, bearing in mind whether the data were 'detailed' or not, we then referred to categorization of the offset data as 'reliable'. If data were not detailed, it would not be possible to estimate uncertainties under questions 3 and 4, so we still had to assume large uncertainties. In these cases, reliable data were assumed to be approximately half as uncertain as unreliable data. Conversely, if data were detailed, different pathways were followed under the protocol for whether the data were 'reliable' or not, in relation to question 3.

Under question 3, data were assigned an initial uncertainty depending on whether they were reliable or not. Then, for each set of offset data in such cases, we considered whether the area occupied by the offset was open to interpretation. Different interpretations would include what to include within the 'area' of an offset (for example, whether the offset involved a set of actions on specific land parcels contained within a larger area). We took the highest and lowest possible area according to different interpretations, and treated that interpretative uncertainty (σ_3) as an amount by which to increase the initial uncertainty, before moving on to question 4.

Under question 4, in the case of all offset data for which this last question could reasonably be asked (otherwise, the overall uncertainty estimate was considered dominated by sources of uncertainty arising under questions 1 and 2), we assumed an additional uncertainty in the evaluation of losses and gains as a result of measurement error. Where estimates of measurement uncertainty existed, we took that value (for example, this has been explicitly calculated for Australian offsets by ref. [44]) (σ_4). Otherwise, we assumed a basic measurement error $\sigma_4 = 10\%$. We incorporated this uncertainty into the uncertainty bound developed under question 3, to give the overall uncertainty estimate.

Decision process. Based on data quality and the categories of uncertainty discussed above, the decision process for estimating uncertainty bounds by individual dataset (that is, for each country or policy driver) was therefore as follows (Supplementary Fig. 1). Again, uncertainty bounds were calculated as a percentage of the estimated value unless otherwise specified.

(1) If a specific offset dataset is not complete, assign an uncertainty of 100% (that is, a coverage factor of 2), whether detailed or not. If the dataset is complete, go to (2):
(2) If the dataset is not detailed or reliable, assign an uncertainty of 100%. If the dataset is not detailed and is reliable, assign an uncertainty of 50% (coverage factor = 1.5). If the dataset is detailed, go to (3);
(3) If the dataset is not reliable, assume that uncertainty is 25% (coverage factor = 1.25) plus the interpretative uncertainty in the data, and go to (4). If the dataset is reliable, assume the uncertainty is equal to the interpretative uncertainty in the data, and go to (4);
(4) If an estimate of measurement uncertainty is available, use that estimate. Otherwise, assume the measurement uncertainty is 10%. In both cases, add this percentage to the existing uncertainty bounds taken from (3).

Uncertainty bounds in the overall areal estimate were calculated by taking the square root of the sum of squared uncertainty bounds for all constituent entries in the database.

Data availability

All biodiversity offset data have been collated into a single database that accompanies this article. The database is available from the corresponding author upon request, and will also be included within the IUCN Global Inventory of Biodiversity Offset Policies (https://portals.iucn.org/offsetpolicy/). Specific sources for each entry, including URLs, are listed in the database.

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Author contributions

J.W.B. conceived of the study, developed the methodology, collected and analysed the data, and wrote the manuscript. N.S. developed the methodology and wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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