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

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Short title: *Biodiversity offsets implementation*

Key words: *Biodiversity offset; conservation evidence; environmental policy; implementation; mitigation hierarchy; no net loss*

Article type: *Analysis*

Word count: *Bold paragraph = 146; main text = 3,719; methods = 2,974. Number of references = 46. Number of figures = 3; number of tables = 1.*

‘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, firstly, that offsets occupy an area up to two orders of magnitude larger than previously suggested: 12,983 offset projects extending over $\mathbf{153,679^{+25,013}_{-64,223}}$ km^2 across 37 countries. Secondly, 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. Thirdly, 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 21st Century [1]. Impacts associated with economic development (e.g. agricultural expansion, infrastructure development, urbanization, 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 [4, 5] to as many as 108 [6] 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 [7]. 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 [8, 9]. Nonetheless, NNL policies (and particularly biodiversity offsets) have generated much interest amongst conservationists and policymakers, in turn becoming the subject of extensive research [10].

Implementation of No Net Loss biodiversity policies

Yet despite 40 years of policy evolution, there has so far been no comprehensive worldwide assessment of the scale upon which conservation activities arising via NNL policies have actually been carried out, nor how they are distributed [4, 11]. 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 e.g. 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 analyses of implementation have to date focused on specific projects (e.g. [12-14]) or subnational regions (e.g. [15]). 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 ultimately, 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].

However, simultaneously mapping the implementation of all components of the mitigation hierarchy enforced under NNL policies is not currently technically feasible (see [16] on ‘avoidance’ measures in US NNL policy). Biodiversity offsets (‘offsets’), however, 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 a 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 find evidence for 12,983 biodiversity offset projects that are currently completed or in the process of implementation, occupying at least $153{,}679^{+25{,}013}_{-64{,}223}$ km^2 worldwide (note the asymmetrical positive and negative uncertainty bounds). For context, the previous best estimates of global offset coverage by area were ~ 2,000 km^2 and ~ 85,000 km^2 [17], and the largest global offset dataset previously constructed contains 70 offset projects [18], though not all offsets included had commenced implementation in any of these cases. The offset projects in our database (Supplementary Information 1) range in size from those that occupy a negligible area to one that occupies some 50,000 km^2 (the latter being associated with the Oyu Tolgoi mine in Mongolia, an areal figure which 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, the Uatumã Biological Reserve in Brazil (compensating for the Balbina hydropower plant), and the Saigachy reserve in Uzbekistan (compensating for multiple extractive sector activities) – together constitute ~ 43% of the total areal estimate in the database (Supplementary Information 1). Though these large projects represent a substantial proportion of that areal estimate, the median area occupied by offsets is 0.021 km^2, and the overwhelming majority (92.9%) of offset projects are small, in that they occupy an area < 1 km^2.

Geographical distribution

Geographically, offset projects can be found on every major continent except Antarctica (Fig. 1A; 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 [10] – and, perhaps unsurprisingly, these regions also feature high numbers of offset projects (Australia, n = 395; Canada, n = 473; Western Europe, n = 1,824; the US, n = 1,729; Fig. 2; Table 1). However, even though the data obtained are less detailed and reliable (according to our definitions of those 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 km^2, 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 [19], Colombia [20], and Mexico [21] – the region has proportionally received less intensive research attention than elsewhere [10, 22]. Combined with the recorded offset activity in Africa (13,684 km^2) and Asia (64,127 km^2, a figure which 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 obtain point locations for 3,416 of the offsets in the database (Supplementary Information 1), providing the opportunity to map offset implementation on a finer (i.e. sub-national) 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 [23] 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 km^2, compared to 81,028 km^2 occupied by those 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 8 projects have so far commenced implementation as a direct requirement from the International Finance Corporation under their Performance Standard 6 (IFC PS6; [24]), despite the fact that PS6 is highly influential and widely considered best practice [25].

Biodiversity offset activities

Biodiversity offsets are considered typically to seek to achieve NNL either through active ecosystem restoration or through the prevention of anticipated biodiversity losses ('avoided loss' offsets), both of which result in biodiversity gains depending upon 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 – though they constitute 69% of offsets in South Africa, and likely a higher proportion in Australia when accounting for unknowns (see [26]). 'Other' activities (e.g. financial offsets) are much less widely observed (Table 1). Regarding largescale regional spatial trends, the majority of offsets in North America, Europe and China implement ecological restoration activities, whilst avoided loss activities represent a greater proportion of offsets in the southern hemisphere (Australasia, sub-Saharan Africa).

Habitat types

The majority of offset projects are implemented in forests (66.7%) or wetlands (17.5%), though 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, North America; Table 1) which are the source of much of the published academic literature on offsets [10].

Regarding that 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 eco-regions defined by the World Wildlife Fund. The relevant shapefiles were obtained through The Nature Conservancy's spatial data repository [27], and offset point locations overlaid upon eco-region polygons in the open access software Quantum GIS. The analysis confirmed that offsets have been implemented across the full range of terrestrial eco-regions, 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 [17, 18] claim to be a comprehensive evaluation, so 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 ten thousand projects occupying an area of over one hundred thousand square kilometers – an important outcome in itself. The implication is that, despite hundreds of journal articles on the topic [10], the global offset portfolio has grown more quickly and is far more widespread than could previously have been realized. By way of comparison, the offset portfolio captured by our database is currently ~ 1% the size of the global terrestrial protected area network [28], though the first offset policies were only developed in the 1970s [4]. We note that the conservation outcomes of offsets, and their contribution towards a NNL objective, cannot be determined based upon the area they occupy alone. However, the fact of this rapid and widespread growth 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.

Further, we demonstrate that there is substantial variation in the density, extent and type of offset project by geographical location and by 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 (e.g. associated policy driver, 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 upon the bulk of the extant offset portfolio by extent (South America, Africa and Asia) rather than where it currently rests (North America, Europe, Australia [10]).

To a first approximation, all offset projects have so far arisen through regulatory requirements. Examination of our database (Supplementary Information 1; see also Fig. 1, Table 1) suggests that regulatory NNL-type policies result in networks of small offset sites, likely with limited landscape-scale coordination. An important 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 [29]). The latter point deserves further research attention (see ‘further uses’).

Our database does suggest that financial lender safeguards (including, but not limited to, IFC PS6) and voluntary corporate commitments [see 30] 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 those projects in Madagascar, Mongolia and Uzbekistan – developers will apparently countenance rather enormous and ambitious conservation interventions if project finance requirements do 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.

Data limitations

The global offset data presented here range widely in quality – from those obtained via detailed, likely comprehensive and reliable government registers (e.g. Australia), to those inconsistently regionally collated via reliable and detailed registers (e.g. Germany), to incomplete headline figures in the grey literature (e.g. China). An important component of our results is consequently the estimates of uncertainty bounds in the area occupied by offset projects, via the application of a systematic protocol (see Methods). Though necessarily estimated, these bounds illustrate the degree of uncertainty in our overall estimate for the area 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). To 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 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 (e.g. the Inter-American Development Bank) were typically accompanied by English language documentation. Offsets implemented in response to national regulation were less straightforward: whilst for key countries (e.g. Brazil, Mexico) some information is available in the English-language literature, those 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 [11]. Data collected for Sweden were contrasted with a comparable national study published in English [31], confirming that those findings were on a reasonable order of magnitude. UK data are available in English. A previous study suggests that most offsetting activity in Europe would be captured via these languages alone [32]. 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 [4, 6] suggest that most offsets currently implemented (with the exception of South Africa) result via lender or corporate requirements. For such projects, project documentation was 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 on keywords in English, the authors were able to utilize Russian language skills to interpret information on offsets in Russia and the former Soviet states (e.g. Kazakhstan, Uzbekistan). Extensive English language literature is available for the major offset project in Mongolia (Table 1). Conversely, China and Southeast Asia were problematic regions for our study 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 sum – whilst 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). Whilst 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 [33]. Furthermore, using chain referral could feasibly have introduced biases to our data collection e.g. if our extended network of offset researchers has 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 e.g. 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 (though 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 [11], and highlight the importance of the progress made in the present study. We considered problems with accessibility when developing our uncertainty protocol (e.g. uncertainties concerning the degree of completeness in the data; 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 first global sampling frame for use in inferential offset research, and a foundation upon 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 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 i.e. implementation. Our (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. The latter would require on the ground assessment of all or 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, 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 [34], or for spatial proximity between developments and associated offsets [35]. Issues like these, concerning whether to permit flexibility in offsetting [36], 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; Supplementary Information 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, then policymakers should be concerned about a transfer of biodiversity value into private ownership. Whilst 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 [37].

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 e.g. avoidance measures. Yet, impact avoidance might be considered the key objective for NNL by conservation stakeholders [13, 14, 16]. 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 endeavor would require substantial investment and resources to undertake, 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 in which 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, which 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" [38]. 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 [4]) that No Net Loss (NNL) is primarily enabled through three drivers: (a) government policies; (b) project finance performance requirements; and, (c) internal corporate policies. Accordingly, our census incorporated offsets implemented (a) within the relevant countries (n = 69; [4]), (b) via projects financed by the relevant development banks or members of the Equator Group (n = 6 and n = 92 respectively; [39]), and (c) companies with known NNL-type corporate policies (n = 32; [30]). Note that, according to the newly developed GIBOP database [6], the number of countries that have policy in place which enables biodiversity offsets (Stages 2 – 3, according to the GIBOP 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 a NNL objective, i.e. "(1) they provide additional substitution or replacement for unavoidable negative impacts of human activity on biodiversity, (2) they involve measurable, comparable biodiversity losses and gains, and (3) they demonstrably achieve, as a minimum, no net loss of biodiversity" [9]. For the avoidance of doubt:

- We include all offsets that arise from policies with a specific NNL objective and which attempt to evaluate full and quantifiable compensation for development impacts (e.g. US wetland banking);
- We include 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 i.e. an implicit NNL objective (e.g. the UK pilot biodiversity offset policy). This recognises that in some instances offsets can arise in the absence of a clearly stated NNL goal; and,

- We do not include any offsets implemented under a policy that has no requirement for full and quantifiable compensation for development impacts (even if a NNL objective is claimed). This recognizes that even if a policy does have 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 at least commenced physical implementation. We excluded any offsets that had been designed but for which delivery has 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 information (Supplementary Information 2).

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 upon 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 [35]. However, we consider data on the number and area of offsets useful proxies for assessing global offset activity, if not outcomes.

Data collection

In order 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 (a) for each relevant subnational region, each country, each multinational region, (b) each financial lender, and finally (c) 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 [40], 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 (e.g. “Australia”, “Rio Tinto”, etc.). That is, we combined each of the 6 fuzzy search terms with: (a) each of the 69 countries; followed by (b) each of the 98 lenders implementing safeguards (n = 6) or belonging to the Equator Group (n = 92); followed by, (c) each of the 32 corporations with stated NNL-type commitments. In sum, this meant that 1,194 separate searches were completed 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 (i) no further relevant data were found or (ii) we reached the tenth page of results (whichever came second).

Expert chain referral

To complement the data review process above and provide a degree of independent validation [38], 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 those data are included in the database. Wherever we were informed that additional offsets had been implemented, but either (a) no documentation was available to confirm the fact or (b) analyses based upon the data could not be published, we excluded the data from our database (Supplementary Information 2).

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. Where offset point locations were described qualitatively in a register or displayed visually online, we extracted approximate latitude/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: (a) management activities associated with implemented offsets (‘offset activities’); and, (b) habitats targeted by offsets. The reasons are:

(a) 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 (e.g. [41, 42]; and see [43] on counterfactuals). It has also been suggested that avoided loss offsets could pave the way for perverse outcomes such as overestimation of offset gains [26]. In building the dataset, we therefore recorded whether offsets involved ‘avoided loss’, ‘restoration’, or alternatives as the primary offset activity;

(b) 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 [9]. Further, some habitats are difficult or impossible to restore [41]. Thus, concerns remain that offsetting is inappropriately applied in practice to certain habitats e.g. old-growth [42]. We therefore captured information on specific habitat types, subsequently grouping these into key categories (e.g. wetland, grassland).

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

Uncertainty protocol

The uncertainty protocol proposed and described here applies to 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 ISO guidelines on Uncertainty of Measurement [44] and so describes the measurement of the data quality, the sources of uncertainty, and the 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 (i.e. the uncertainty bound is effectively an un-quantified 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 upon informed estimates concerning the accuracy of the information contributing towards 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/policy driver is 100% of the value stated – such that the confidence interval runs between coverage factors x0 and x2 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 (‘unknowns unknowns’) 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 likely an underestimate. By not incorporating this as a potential bias into our uncertainty estimates (i.e. through the use of asymmetrical uncertainty bounds), we again seek to ensure that our overall estimates are 'conservative' (i.e. if at all inaccurate, then most likely *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' below), 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 have 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 total offset area globally.

<u>Data quality</u>

We begin with an assessment of data quality, based upon the sources consulted. This assessment was structured around three categories, capturing whether (Y/N) the data could be considered (i) detailed, (ii) complete, and (iii) 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 (e.g. specific management activity, spatial extent, point location, habitat impacted, etc.). 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 (e.g. an Environmental Impact Assessment and associated offset strategy); subject to accredited third party verification (e.g. offsets implemented as part of certain development bank finance requirements); or, peer-reviewed academic literature.

Sources of uncertainty

Regan et al. [45] 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:

(Q1) Have we captured all offset projects, and have we captured them in detail [epistemic]?

(Q2) Are the offsets we have captured overestimated or falsely claimed [linguistic]?

(Q3) Are there different possible interpretations for the area occupied by the offsets we have captured [linguistic]? and,

(Q4) How accurate is the numerical information we have on those offsets [epistemic]?

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

Under question (Q1): we referred to the categorization of offset data as 'detailed' and 'complete' (see section above on data quality). Whenever offset data were not considered 'complete', we assume uncertainty to be very large (i.e. the maximum possible under our protocol). For data that were complete, different pathways were then followed under the protocol if the data were 'detailed' or not, in relation to question (Q2).

Under question (Q2): bearing in mind whether the data were 'detailed' or not, we then referred to the categorization of the offset data as 'reliable'. If data were not detailed, then it would not be possible to estimate uncertainties under questions (Q3) and (Q4), so we still had to assume large uncertainties. In those 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 if the data were 'reliable' or not, in relation to question (Q3).

Under question (Q3): data that were assigned an initial uncertainty depending upon 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 (e.g. if 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 initial uncertainty, before moving on to step (4).

Under question (Q4): finally, 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 Q1 and Q2), we assumed an additional uncertainty in the evaluation of losses and gains as a result of measurement error. Where estimates of measurement uncertainty exist, we took that value (e.g. this has been explicitly calculated for Australian offsets by [46]) ('σ_4') – otherwise, we assume a basic measurement error $\sigma_4 = 10\%$. We incorporate this uncertainty into the uncertainty bound developed under question (3), to give the overall uncertainty estimate.

<u>Decision process</u>

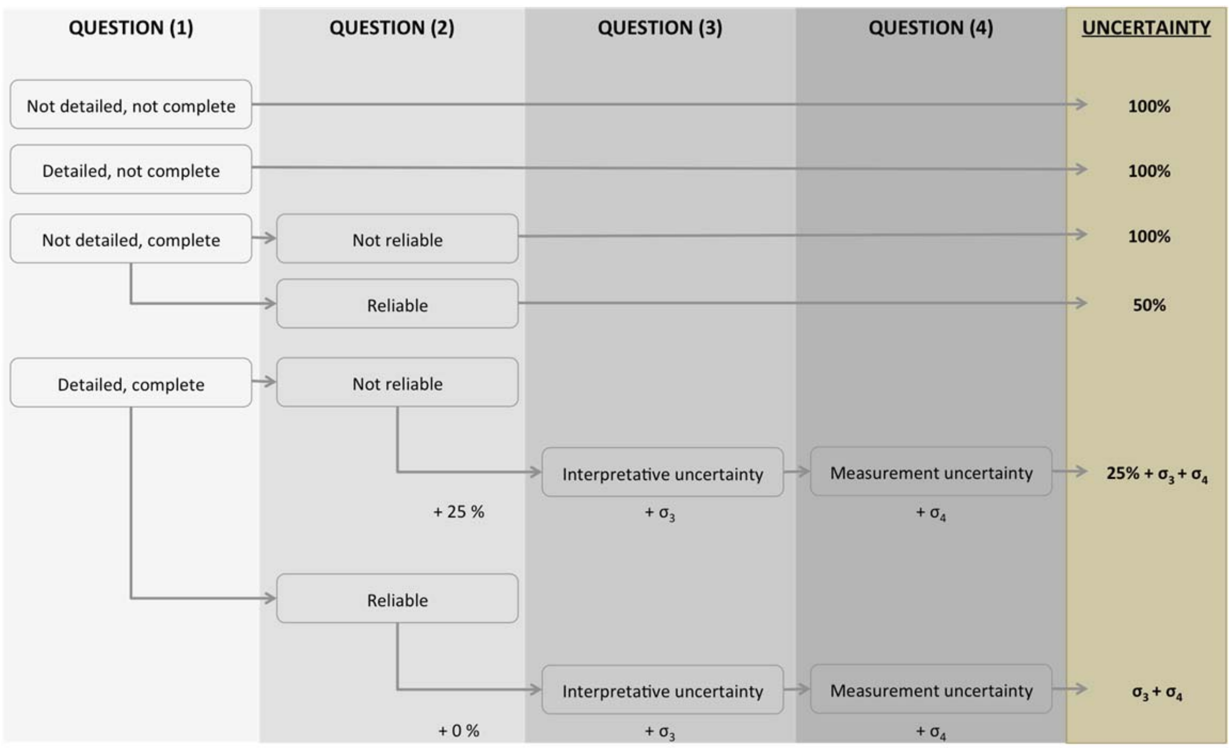
Based upon data quality and the categories of uncertainty discussed above, the decision process for estimating uncertainty bounds by individual dataset (i.e. for each country or policy driver) was therefore as follows (Fig. M.1). Again, uncertainty bounds were calculated as a percentage of the estimated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

(1) If a specific offset dataset is not complete, assign an uncertainty of 100% (i.e. a coverage factor = 2), whether detailed or not. If the dataset is complete, go to (2);
(2) If the dataset was not detailed and is not reliable, assign an uncertainty of 100%. If the dataset was not detailed and is reliable, assign an uncertainty of 50% (coverage factor = 1.5). If the dataset was 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 measurement uncertainty is 10%. In both cases, add this percentage to the existing uncertainty bounds taken from (3).

Figure M.1*: decision process for estimating uncertainty bounds. Uncertainty given as a percentage of the estimated value of total biodiversity offset area for the dataset corresponding to each country/policy driver*



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 which 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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Acknowledgments

We thank all those consulted (Supplementary Table 1) for supporting construction of the database. J.W.B. was funded by a Marie Skłodowska-Curie Action under the Horizon 2020 call H2020-MSCA-IF-2014 (grant number 655497). J.W.B. and N.S. acknowledge the Danish National Research Foundation for funding for the Center for Macroecology, Evolution and Climate (grant number DNRF96).

Author contributions

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

Competing Interests Statement

The authors declare no competing financial interests.

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

Figure 2: *Key characteristics of biodiversity offsets extracted from our database. For all countries with some record of implementation, the number ($\log_{10}$) and area (km^2) of biodiversity offsets is given. Uncertainty in the value of area occupied was estimated on the basis of our uncertainty protocol (see Methods) and is displayed on the figure. Pie charts show, by country, the main 'Activity' (conservation management activity) and 'Habitat' (habitat type) associated with offsets, for which the proportion is based on the total number of offsets in that country. ND = no data.*

Figure 3: *(**a**) Frequency distribution of all biodiversity offsets in the database associated with areal information, by area occupied (km^2). Inset = equivalent frequency distribution for the subset of offsets driven by either project finance requirements or voluntary corporate commitments. The mean area occupied by offsets for projects driven by public policy versus those driven by lender and corporate requirements is substantially different (means = 48.5 km^2 and 3,100.4 km^2 respectively). (**b**) Fish habitat restoration offset in Canada. (**c**) Grassland restoration offset in Australia. (**d**) Mammal conservation ('avoided loss') offset in Uzbekistan (photo credits: J. W. Bull).*

***Table 1**: Country summaries from the biodiversity offset database. Includes: the number of offsets recorded; the area they occupy (uncertainty in the value of area occupied was estimated on the basis of our uncertainty protocol – see Methods); offset activity by percentage of total number of projects ('Av. L.' = avoided loss offsets, 'Rest.' = restoration offsets, 'Both' = a combination of avoided loss and restoration-based offsets); and, habitat type in which the offset is implemented, by percentage of total number of projects ('Grass.' = grassland, 'Wetl.' = wetland). ND = no data.*

Country	Number biodiversity offsets	Area biodiversity offsets (km^2)	Management activity (%)					Habitat type (%)				
			Av. L.	Rest.	Both	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	53 ± 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

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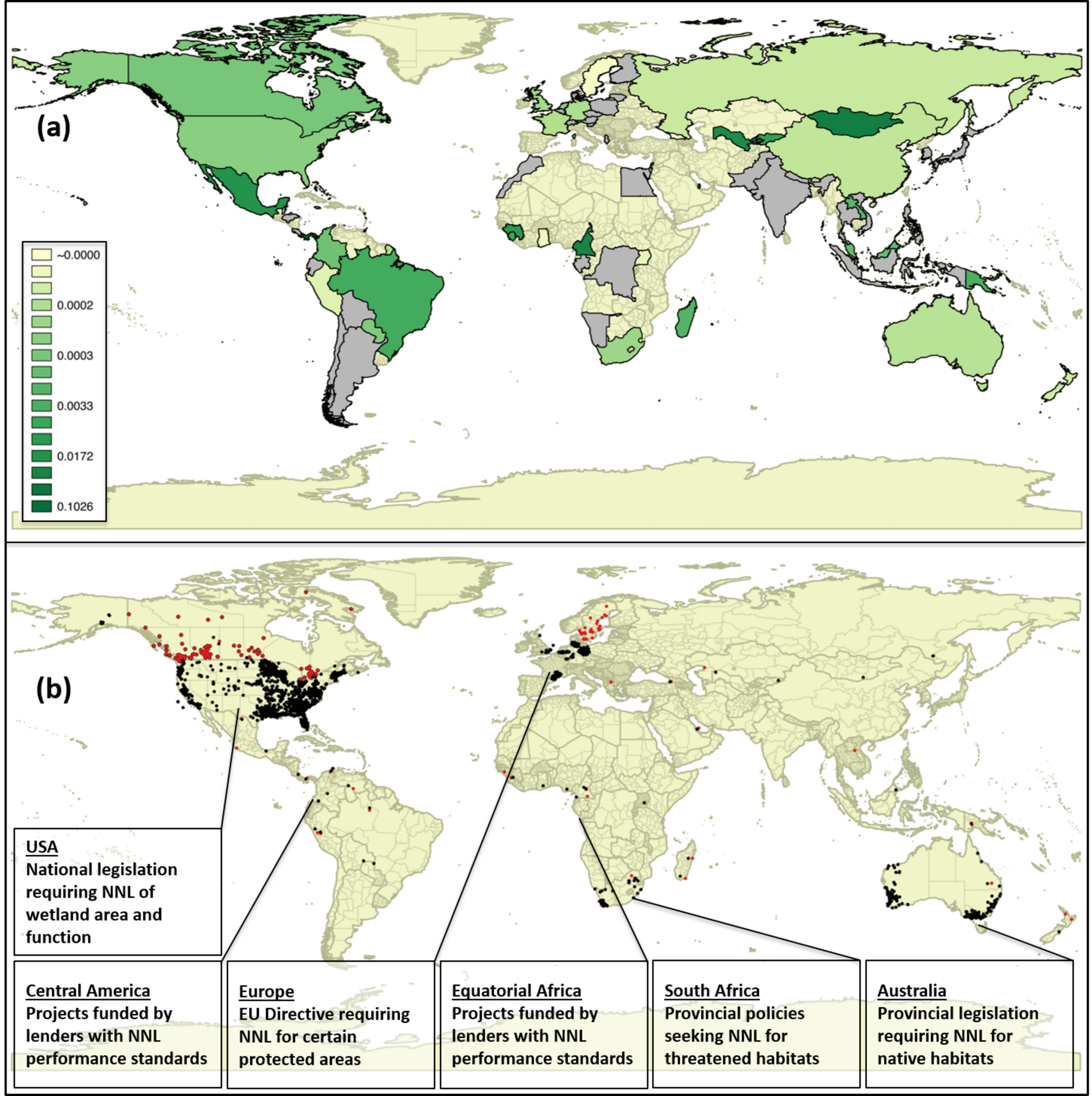
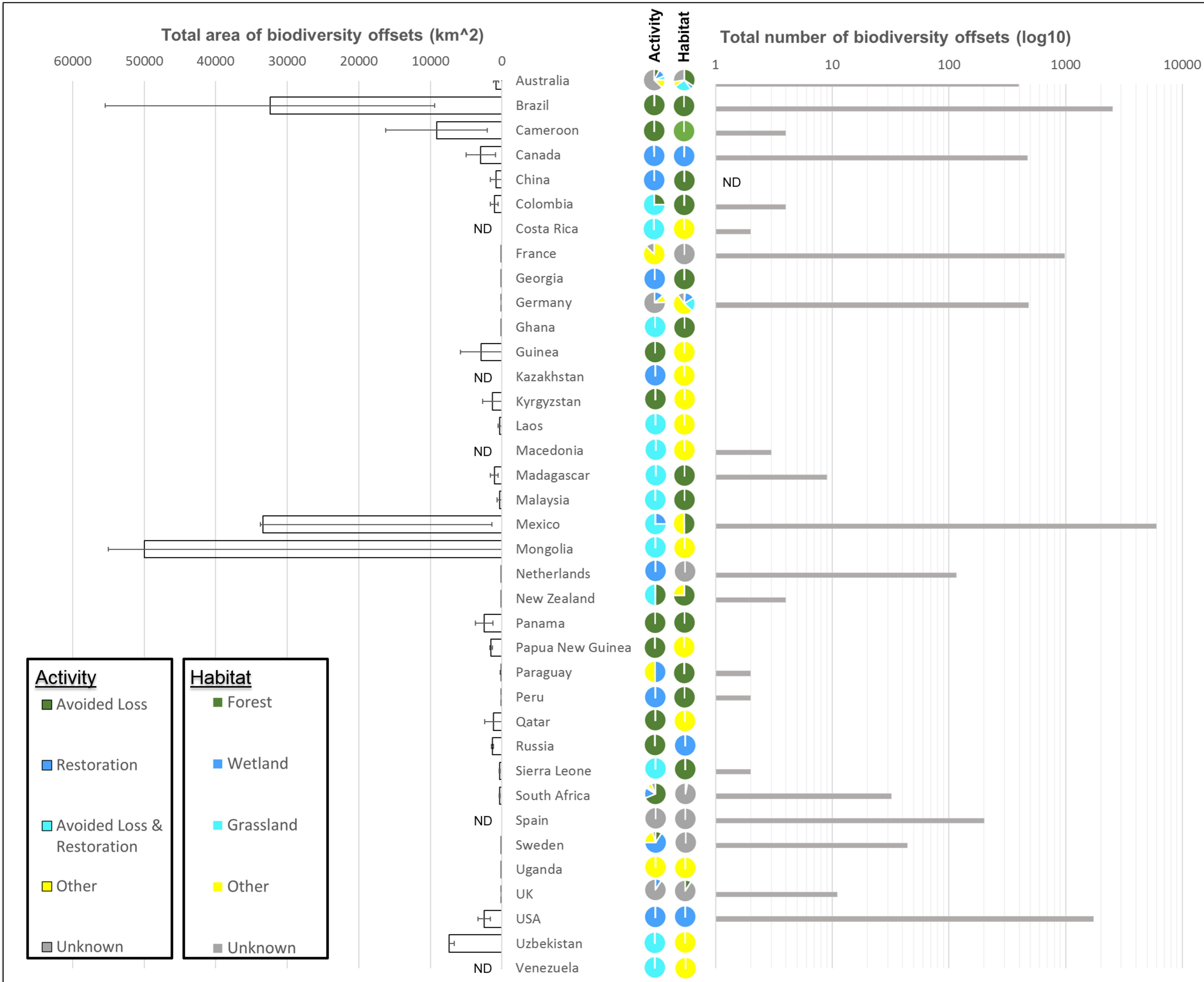
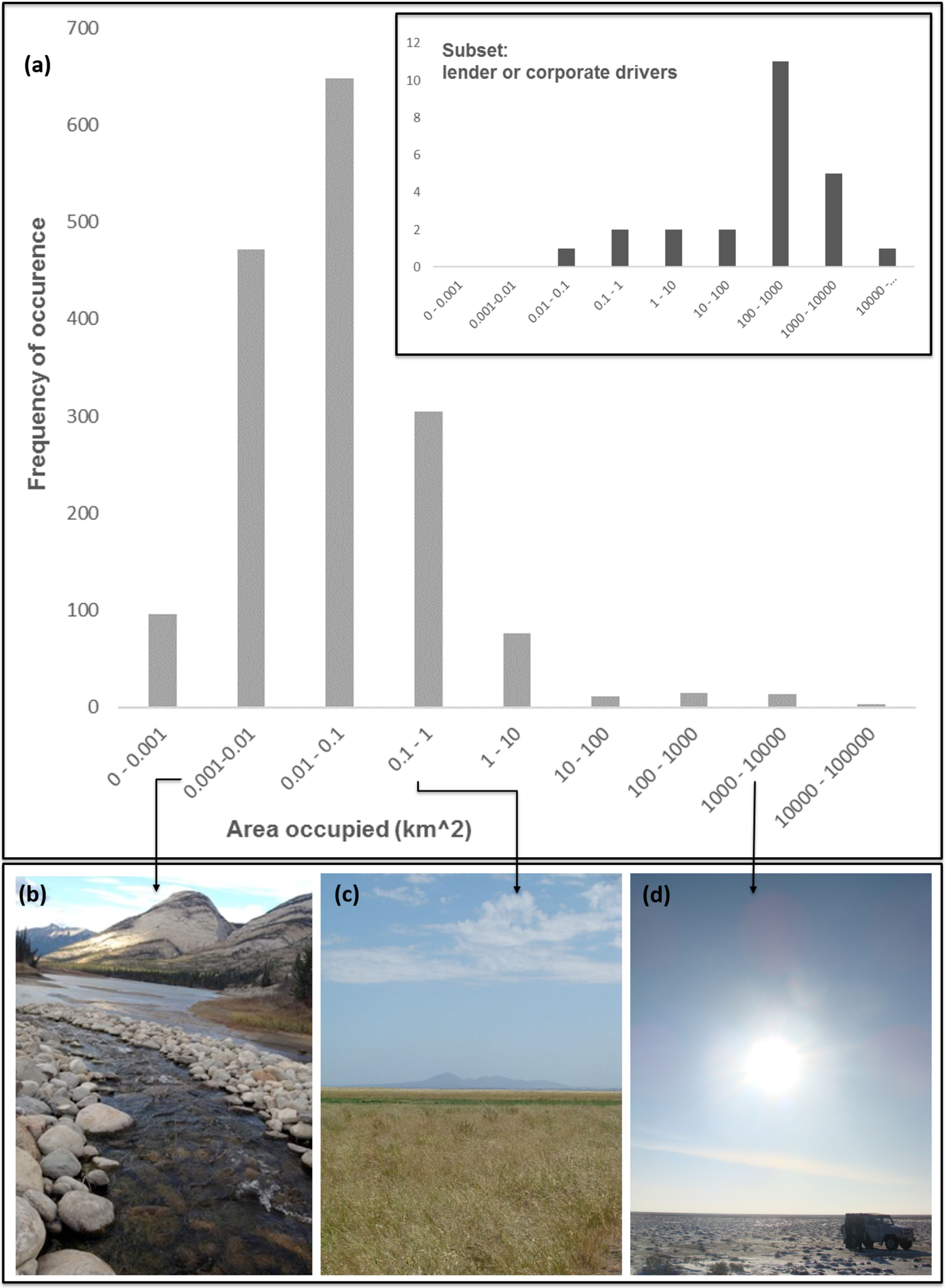


(a)
~0.0000
0.0002
0.0003
0.0033
0.0172
0.1026
(b)
USA
National legislation requiring NNL of wetland area and function
Central America
Projects funded by lenders with NNL performance standards
Europe
EU Directive requiring NNL for certain protected areas
Equatorial Africa
Projects funded by lenders with NNL performance standards
South Africa
Provincial policies seeking NNL for threatened habitats
Australia
Provincial legislation requiring NNL for native habitats



Total area of biodiversity offsets (km^2)
60000
50000
40000
30000
20000
10000
0
Activity
Habitat
Total number of biodiversity offsets (log10)
1
10
100
1000
10000
Australia
Brazil
Cameroon
Canada
China
ND
Colombia
ND
Costa Rica
France
Georgia
Germany
Ghana
Guinea
ND
Kazakhstan
Kyrgyzstan
Laos
ND
Macedonia
Madagascar
Malaysia
Mexico
Mongolia
Netherlands
New Zealand
Panama
Papua New Guinea
Paraguay
Peru
Qatar
Russia
Sierra Leone
South Africa
ND
Spain
Sweden
Uganda
UK
USA
Uzbekistan
ND
Venezuela
Activity
Avoided Loss
Restoration
Avoided Loss & Restoration
Other
Unknown
Habitat
Forest
Wetland
Grassland
Other
Unknown



(a)
Frequency of occurence
700
600
500
400
300
200
100
0
0 - 0.001
0.001-0.01
0.01 - 0.1
0.1 - 1
1 - 10
10 - 100
100 - 1000
1000 - 10000
10000 - 100000
Area occupied (km^2)
Subset:
lender or corporate drivers
12
10
8
6
4
2
0
0 - 0.001
0.001-0.01
0.01 - 0.1
0.1 - 1
1 - 10
10 - 100
100 - 1000
1000 - 10000
10000 -...
(b)
(c)
(d)