An integrative approach to implementing biodiversity net gain at the regional level

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Abstract

Biodiversity offsetting has emerged as an increasingly popular policy tool aiming to ensure that housing development associated with urban expansion can benefit nature. Offsets compensate for biodiversity losses from development by creating, restoring, or enhancing habitats, aiming to achieve either no net loss or a net gain in biodiversity. The effectiveness of this approach depends not only on the quantity and condition of the offsets but also on their spatial placement, which can be either on the development site or elsewhere. We present a spatially explicit modelling framework designed to explore how offset location affects biodiversity outcomes and ecosystem service co-benefits at the regional scale - the scale at which infrastructure planning decisions are generally made - using an English region (Buckinghamshire and Oxfordshire) undergoing significant housing growth as a case study. Findings reveal that closest proximity-driven offsetting underperforms in terms of biodiversity outcomes (species richness) and opportunity costs of agriculture. In contrast, regional prioritisation aligned with strategically planned conservation networks (i.e., regional Nature Recovery Networks), delivers the greatest increase in species richness (12%) and lower opportunity costs. In separate scenarios, restricting offsets to administrative planning boundaries yielded even lower opportunity costs and higher values for co-benefits (carbon sequestration and flood damage avoided costs), although this restriction resulted in a smaller percentage increase in species richness. These results demonstrate the value of strategic planning in guiding biodiversity offsetting implementation and highlight the potential for Nature Recovery Networks or similar conservation networks to enhance biodiversity outcomes at the regional scale.

1. Introduction

Rapid urban expansion is contributing to biodiversity loss through habitat conversion, fragmentation, and degradation. Projections indicate that continued urban growth could result in extensive natural habitat loss, reduced species richness and abundance (Li et al., 2024), and increased pressure on protected areas (McDonald et al., 2008), underscoring the urgent need for sustainable urban planning. In response to these threats, biodiversity offsetting has emerged as a popular strategy to compensate for 'unavoidable' biodiversity losses caused by development projects (Bull et al., 2013; Gonçalves et al., 2015). Biodiversity offsets are actions that restore, enhance, or protect biodiversity to compensate for the losses from development (Bull et al., 2013). This approach seeks to achieve either neutral biodiversity outcomes (i.e., No Net Loss; NNL), or positive outcomes (i.e., Biodiversity Net Gain; BNG), compared to pre-development baselines

(McKenney & Kiesecker, 2010). As countries seek to balance the need for housing and infrastructure with national and international targets for biodiversity recovery, mandatory net gain policies could become more widespread (zu Ermgassen et al., 2022).

Both conceptual and practical challenges impede the effective implementation of biodiversity offsets (Bull et al., 2013; Gonçalves et al., 2015). Biodiversity offsets can be placed within the planned development (i.e., onsite) or elsewhere (i.e., offsite). Conceptually, offsite offsets could deliver greater benefits (both in terms of biodiversity and other services), particularly if aligned with landscape or regional conservation strategies (Gonçalves et al., 2015; Gordon et al., 2011; Kujala et al., 2015; Mancini et al., 2024; Underwood, 2011). For example, offsite offsets could be used to implement conservation actions in locations that will have the greatest benefit for a species in terms of its viability at the landscape level (Shumway et al., 2023). However, in practice, the implementation of offsite offsets raises questions about the substitutability of biodiversity and the loss to local communities of the benefits of access to biodiversity (Maron et al., 2016). Onsite offsets can, in principle, mitigate the damage to biodiversity within the impacted area itself (Gonçalves et al., 2015; McKenney & Kiesecker, 2010) and in some cases help compensate for the loss of the benefits for local people (Jones et al., 2019; Moreno-Mateos et al., 2015; Tupala et al., 2022). However, recent evidence from both national (Faccioli et al., 2025) and local (Butler et al., 2025) choice experiments suggests that proximity to the development is not necessarily a key factor in public preferences. These findings challenge assumptions about the social benefits of onsite and local offsetting.

Given the onsite vs offsite debate, and to ensure the future success of biodiversity offsetting schemes in delivering NNL or BNG, a better understanding of where to place offsets is needed, particularly how placement can affect the offsets' associated benefits. Research addressing this gap in understanding is gaining momentum. For example, in the United States, empirical comparisons of the flood alleviation ecosystem services (ES) delivered by wetland offsets found that on-site compensation projects were associated with higher value than off-site wetland mitigation banks (Vaz et al., 2026). On the other hand, in England, national-level insights have revealed that the local offset approach, where offsets were placed at a minimum distance from the development, performed relatively poorly in terms of the potential environmental and social benefits that could be delivered (Mancini et al., 2024). National-scale studies recognise the significance of national strategic action to achieve national and international targets for nature recovery (i.e., the broader spatial perspective within which offsetting operates). However, the national lens can overlook distinct regional landscapes with distinct ecological and societal needs. Local-scale studies can guide the implementation of particular individual projects. For example, Atkins et al. (2025) showed that a range of options exist for offsite offsets that could fulfil a range of different criteria important for local people and biodiversity. However, in many countries, key planning decisions and nature recovery targets are set at the landscape or regional level, rather than nationally or at the individual project level. Therefore, a better understanding of the potential benefits of different offsetting scenarios at a regional level is needed to more effectively support decision-making which is made at this crucial, policy relevant scale.

In this paper, we develop a spatially-explicit modelling framework to explore regional-scale offsetting scenarios, incorporating regional planning restrictions, requirements, and conservation strategies. We apply our framework in England, the first country to legally mandate a 10% biodiversity uplift for most housing developments, effective since February 2024 (Ministry of Housing Communities and Local Government & Department for Levelling Up Housing and Communities, 2024). With other countries considering similar approaches, England offers a timely and relevant context. Alongside mandatory BNG, England is developing a nationwide system of local nature recovery strategies (LNRS) to guide the development of nature recovery networks (NRNs), designed to help meet commitments to improving the state of its nature by 2042, and to protect 30% of land by 2030 (Department for Environment, Food and Rural Affairs, 2023a). These national-level commitments make England a compelling case study to explore how BNG can be integrated with other environmental policies at a regional level – the scale at which planning decisions are generally made. We use our framework to estimate the changes in biodiversity (using species richness as a proxy), alongside other ES associated with change in land cover - opportunity cost of agriculture, carbon sequestration value, flood damage avoided costs, and access to public greenspace - under four scenarios. Understanding of wider environmental net gains is a recognised ambition of English environmental policy (Department for Environment, Food and Rural Affairs, 2023a). By estimating these wider ES within our framework, we offer a more holistic understanding of the trade-offs and synergies involved in implementing BNG at a regional scale.

2. Methods

To explore the spatial dynamics of biodiversity offsetting at the regional scale, we developed a structured analytical framework and applied it to our case study region (Buckinghamshire and Oxfordshire in England). The framework comprises five key steps, each designed to support the spatial modelling process. A visual summary of these steps is provided in Figure 1.

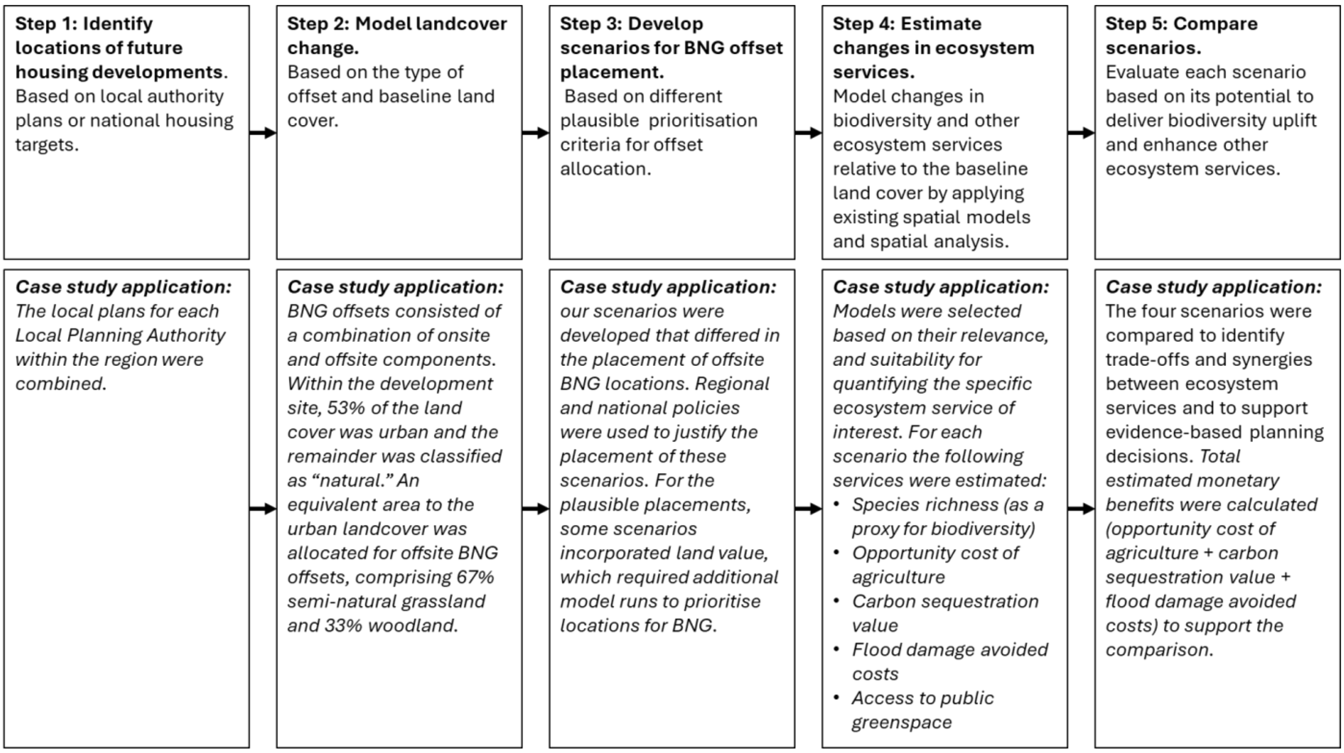

Figure 1: Framework outlining the steps used to explore how the location of Biodiversity Net Gain (BNG) offset sites affects changes in biodiversity and other ecosystem services. The application of each step to the case study region (Buckinghamshire and Oxfordshire) is shown in italics. Further details of the application are provided in the Methods (Sections 2.1-2.5).

2.1. Identify locations of future housing developments

All analysis was undertaken for two adjacent English counties, Buckinghamshire and Oxfordshire, referred to collectively as “the region”. The region covers 4,171 square kilometres and consists of nine Local Planning Authorities (LPAs). The Centre for Ecology and Hydrology (CEH) 25m 2020 Land

Cover Map (Morton et al., 2022) was used as the assumed baseline land cover. The expected number (*n* = 314) and location of future housing developments were taken from the Local Plan data for Buckinghamshire and Oxfordshire (see SI 1 for details). These datasets contained the boundary for each development, commonly referred to as the development's "red-line", beyond which development impacts are not permitted.

2.2. Model landcover change

In all scenarios, BNG offsets were made up in part of onsite and offsite offsets. We assumed that if the combined area of onsite and offsite BNG offsets equalled the area of the corresponding new development (i.e., the area within the red-line), the 10% BNG uplift requirement was met. This is likely to be a precautionary assumption because empirical data suggest that developments have been reaching their BNG requirements with a 34% reduction in overall natural area, due to habitat enhancement (zu Ermgassen et al., 2021). At the time of modelling, the average proportion of natural cover within the red line of completed developments in the region was 47% (Rampling et al., 2024; zu Ermgassen et al., 2021). The remaining 53% of the area within the red-line was classified as "urban". We used this ratio in our models, assuming that 53% of the area of each new development would need to be compensated for via offsite BNG. Based on empirical evidence about how offsite BNG is currently implemented in England (Rampling et al., 2024; zu Ermgassen et al., 2021; Duffus et al. 2025), all offsite BNG sites were placed on agricultural land, and were assumed to be converted into 67% semi-natural grassland and 33% woodland (representative of the region's current land cover). A mix of 60:40 deciduous and conifer woodland cover was assumed. If the development red-line included the land cover classification "water", this was not converted. Instead, it was considered part of the onsite delivery of Biodiversity Net Gain (BNG). In a small number of cases (*n* = 3), developments were located on land already classified as urban. Since urban land could not be converted to natural habitat under the modelling assumptions, it was retained in its existing state, and additional offsite land was allocated to ensure the required biodiversity compensation was met.

2.3. Develop scenarios for BNG offset placement.

We developed four scenarios, which differed according to which offsite BNG locations were selected (Table 1). These scenarios were devised from discussions between the authors and other interested parties working in the BNG policy and implementation space. Their purpose was to represent potential "realistic" scenarios of BNG implementation in England. As such, these scenarios were guided by considerations and constraints of England's BNG Metric 4.0 (Department for Environment Food and Rural Affairs, 2024) the statutory tool applied to calculate biodiversity net gain. As BNG is a condition of planning permission, it is the responsibility of Local Planning Authorities (LPAs) to ensure its implementation. While offsite offsets can be located in a different LPA to the development, the biodiversity metric includes a spatial multiplier that increases the number of required units (Department for Environment Food and Rural Affairs, 2024). The aim of this spatial multiplier is to help keep the potential benefits of BNG offsets within the LPAs or National Character Areas that are experiencing damage and loss of nature from the development. There are other environmental policies that, in practice, could influence the location of offsite BNG offsets in England. Local Nature Recovery Strategies (LNRSs) are being developed at the county level to create nature recovery network (NRNs), which will support LPAs in their development decisions and could be used to identify and prioritise locations for BNG offsets (Department for Environment Food and Rural Affairs, 2023a). To promote alignment between offsets and LNRSs, the BNG metric includes a strategic significance multiplier that applies only to offsets located in areas identified within each LNRS (Department for Environment Food and Rural Affairs, 2024). Table 1 summarises the relevant policy justification and considerations informing each scenario.

Table 1: Biodiversity Net Gain (BNG) offset scenarios and their corresponding assumptions and policy justification for the selection of offsite BNG offset locations.

BNG offset Scenario	**Assumptions determining the location of the offsite BNG offset**	**Justification**
Scenario 1 – Closest offset	Offsite BNG sites were located on the closest (minimum distance) agricultural land to the development's redline.	The minimum distance to the development was a strict application of the proximity principle and incorporated the National Planning Policy Framework's recommendation (para. 186) to improve biodiversity in and around the development (Ministry of Housing Communities & Local Government, 2023).
Scenario 2 – Local offset	Offsite BNG sites were located on agricultural land within the same Local Planning Authority (LPA) as the development. All available sites meeting this criterion were selected according to minimum cost (see Section 2.3 for details).	Restricting BNG sites to the LPA aimed to maximise the potential units from the BNG Metric 4.0; the Metric's "Spatial Risk Multiplier" reduces the score given to BNG offset sites in different LPAs (Department for Environment Food and Rural Affairs, 2024).
Scenario 3 – Local offset to support conservation priorities	Offsite BNG sites were located on agricultural land within a proposed nature recovery network for the region (NRN; Smith et al., 2022) and had the same LPA as the development. All available sites meeting this criterion were selected according to minimum cost (see Section 2.3 for details).	NRN identifies areas to prioritise for nature recovery. NRNs should be used by LPAs to inform their local plans and development decisions (Department for Environment Food and Rural Affairs, 2023a). We restricted the NRN to the same LPA as the development because the BNG Metric 4.0 "Spatial Risk Multiplier" prioritises offsets placed within the LPA by reducing the score given to BNG offset sites in different LPAs (Department for Environment Food and Rural Affairs, 2024).
Scenario 4 – Regional offset to support conservation priorities	Offsite BNG sites were located on agricultural land within a proposed NRN for the region (Smith et al., 2022). All available sites meeting this criterion were selected according to minimum cost (see Section 2.3 for details).	NRN identifies areas to prioritise for nature recovery. Removing the restriction to the same LPA as the development (Scenario 3) enables us to test the effect of not incorporating the Metric's "Spatial Risk Multiplier" on the placement of offsets and the associated estimated benefits.

Scenarios 2-4 required additional information on the minimum cost to inform the placement of offsite BNG (**Table 1**). An additional model iteration was required to obtain this information. For this iteration, all agricultural land cover within the region's baseline landcover (Morton et al., 2022) was converted to the assumed mix of seminatural grassland and woodland (67:33, see Section 2.2). The outputted cost information provided (see Section 2.4.2) was then used to inform the selection of minimum cost locations and develop final scenario landcover maps. The final land cover maps for each scenario were then input into our selected models to estimate the potential benefits of each Scenario.

Activity Scenarios 3 and 4 used a proposed NRN for the region developed by Smith et al. (2022). This NRN was designed using a systematic conservation planning approach developed in collaboration with Berkshire, Buckinghamshire and Oxfordshire Wildlife Trust (BBOWT). The network identified core zones to maintain current biodiversity and recovery zones for habitat restoration. As the aim of the recovery zones was to improve the ecological condition of existing habitats and increase habitat coverage through restoration, they make ideal sites for BNG offsetting. Therefore, for Activity Scenarios 3 and 4, the selection of sites within the NRN (Smith et al., 2022) were prioritised in the following order: "BBOWT Recovery", "Other Recovery", "BBOWT Core", and "Other Core".

2.4. Estimate changes in ecosystem services

To compare the relative performance of the four scenarios, we estimated the change in biodiversity and four additional ecosystem services (ES) resulting from the scenario's assumed landcover change (from the housing developments and associated BNG offsets) compared to the 2020 baseline landcover (Morton et al., 2022). Biodiversity gain was estimated as the change in species richness, and the ES estimated were: (1) carbon sequestration value, (2) flood damage avoided costs, and (3) public access to greenspace. We also calculated total monetary benefits (sum of monetary values estimated in this framework – estimated opportunity cost of land lost to agriculture). Following (Mancini et al., 2024), many of the services were estimated using the Natural Environmental Valuation decision support system (NEV). NEV, which was used for the UK National Ecosystem Assessment (I. J. Bateman et al., 2013; Watson et al., 2011), is a suite of spatially explicit models that quantifies the effects of land use change. Estimates for all the outputs generated in NEV were aggregated to a 400 ha (i.e. 2 km × 2 km) spatial grid, which makes them appropriate to support our comparison of scenarios.

2.4.1. Species richness

Although the Statutory Metric aims to ensure a 10% net gain in biodiversity, it is based on the scoring of habitat size and quality. Biodiversity encompasses other elements, in particular species populations. Recent studies suggest that there is minimal correlation between a site's score on the Statutory Metric and its species richness (Duffus et al., 2024; Hawkins et al., 2022). Therefore, following (Mancini et al., 2024), we explored how offsets would perform against a comprehensive evaluation of the effect of land cover change on a set of 100 species of conservation priority that represent a variety of taxonomic groups, including: birds, herptiles, invertebrates, lichen, mammals and vascular plants (See SI 2 for details). The percentage change in species richness was calculated using the UK Joint Nature Conservation Committee (JNCC) biodiversity modelling framework within NEV, which follows Croft et al. (2017).

2.4.2. Opportunity cost of agriculture

Cost values represented the opportunity costs of converting agricultural land to a BNG site (at the assumed mix of grassland and woodland). Opportunity costs of agriculture were modelled in NEV following the methodology proposed by Fezzi et al. (2015). This methodology utilised data provided by the UK Farm Business Survey and Agricultural Census from the 1960s to the present day to provide spatial estimates of farm profitability. Additional details on data sources, data preparation and model estimation are given in Day et al. (2024).

2.4.3. Carbon sequestration

The total value of carbon sequestration was calculated by summing the estimated values from the NEV forestry timber sequestration model and the NEV soil sequestration model. NEV's carbon sequestration model from above-ground forestry followed a two-stage process. First, the CARBINE model (Thompson & Matthews, 1989) was used to predict the annual timber volumes (considering live wood, deadwood, and harvested wood products) of the tree species given rotation period, yield class, and management regime. We used Pedunculate Oak and Sitka Spruce species as proxies for deciduous and coniferous trees, respectively, and implemented a "thinning and felling" management regime. Within NEV an additional model was applied to predict how forest growth may be affected over time by climate change. The underlying data used in these models included predictions of tree growth under different yield classes, climate projections, soil characteristics, emissions data from livestock, and terrain features. The models produced annual predictions from 2020 to 2060 and incorporated two rotations into the future projections. Discounting was applied to one rotation of tree planting (Day et al., 2024).

The soil sequestration model within NEV estimated the economic value of carbon sequestration resulting from changes in the conversion of agricultural land to woodland (Day et al., 2024). Similar to the forestry timber sequestration model, the CARBINE model was used, and the same split of Oak and Sitka Spruce species and management regime was applied. The CARBINE model provided additional output for below-ground greenhouse gas sequestration, which was estimated using data on soil and land characteristics. This was then converted to an economic value by multiplying the quantity of carbon sequestered by the social cost of carbon (Day et al., 2024). Discounting was applied to two rotations of tree planting to account for the longer-term fluctuations in carbon storage.

2.4.4. Flood damage avoided costs

Expected avoided damage costs to properties were calculated using the flood risk model within NEV (Day et al., 2020, 2024). This model predicted the impact of land cover changes on the likelihood of different extreme flood events (i.e., of varying magnitude), including the 1 in 10, 1 in 30, 1 in 100, and 1 in 1000 year flood events. Predictions were calculated for all sub-catchment areas, as defined by The Water Environment (Water Framework Directive) Regulations (2017), within the region. The economic implications of the change in the probability of extreme flooding events were then calculated by estimating (1) the number of properties (residential and non-residential) susceptible to flooding and (2) their associated flood damage costs from different magnitudes of flooding. The value outputted by NEV was a measure of flood damage avoided costs (i.e., a benefit).

2.4.5. Access to public greenspace

In England, the government has made a national commitment to ensuring that people have access to greenspace within a 15-minute walk from their homes (Department for Environment Food and Rural Affairs, 2023a). The 'sf' package (Pebesma, 2018) in R statistical software (R Core Team, 2024), was used to estimate public greenspace access in the region and explore which areas within the region have achieved this target and how the implementation of Biodiversity Net Gain (BNG) offsets may impact greenspace access. We identified the nearest public greenspace to each Output Area's (the lowest geographical area used for census statistics in England) population-weighted centroid within the Region (n = 3,872). The distance from the Output Area's population-weighted centroid to the corresponding nearest public greenspace was then calculated. To determine greenspace access we applied a distance threshold of 1km, assumed to be the equivalent of a 15-minute walk at a comfortable speed of 1.2 m/s. Output Areas with a greenspace <1km away were classified as having access to greenspace, and Output Areas >1km away from the nearest greenspace were classified as not having access to greenspace. The locations of public greenspace were established using Natural England's England Green Infrastructure Mapping Database Version 1.2 (Moss, 2023), a fine-scale vector dataset of public greenspace in England.

2.5. Compare scenarios

The quantified benefits for each scenario were compared to evaluate their relative performance. For the monetary benefits, the sum of monetary values estimated in this framework minus estimated cost was calculated. As the focus of England's BNG is to deliver a net uplift in biodiversity, we did an additional iteration of the model to establish the potential maximum uplift in species richness (our proxy for biodiversity) in the region based on our modelling assumptions. This enabled us to compare the "realistic" scenarios of BNG implementation in which sites were chosen based on cost and spatial constraints (Table 1) with the maximum potential increase in species richness with no constraints or consideration of cost.

To establish the maximum increase in species richness, a new land cover map was created whereby all available agricultural land cover was converted to a combination of semi-natural grassland and woodland. The change in species richness for this land cover map was estimated using the JNCC model (Section 2.4.1). Locations were then ranked from high to low species richness and a standard ordering algorithm was applied to select the locations for offsite BNG offsets with the highest potential increase in species richness. The ordering algorithm resulted in a second land cover map to which the JNCC model was applied. This second iteration provided an estimate of the theoretical maximum increase in species richness based on our modelling assumption.

3. Results

3.1. Distribution and location of offsets

The 314 developments across the Oxfordshire and Buckinghamshire local plans covered 71.23 km². The equivalent area was allocated to BNG offset sites; 47% onsite (within the development's red-line) and the remainder (53%) was allocated to agricultural farmland offsite according to the scenario assumptions (Table 1).

Figure 2 shows the location of all offset sites for these four scenarios. As expected, Scenario 1, which has offsets closest to the development, shows a uniform distribution around the region's developments, whereas Scenarios 2, 3, and 4 show higher concentrations of offsets towards the centre of the region. Scenarios 2,3,4 all minimise opportunity cost of agriculture and have therefore retained the higher value agricultural land across the region. The change in the offset assumptions to include the NRN (Scenarios 3 and 4), disperses the offset sites more (i.e., a lower concentration of sites distributed across the region) compared to Scenario 2 (no NRN). Removing the within-LPA requirement and just considering the locations of the NRN and minimising cost (i.e., comparing Scenario 4 to Scenario 3) resulted in a new concentration of offset sites in the southeast of the region, alongside the central-region concentration in scenarios 2 and 3 which align with prioritised recovery areas of the NRN set out in Section 2.3.

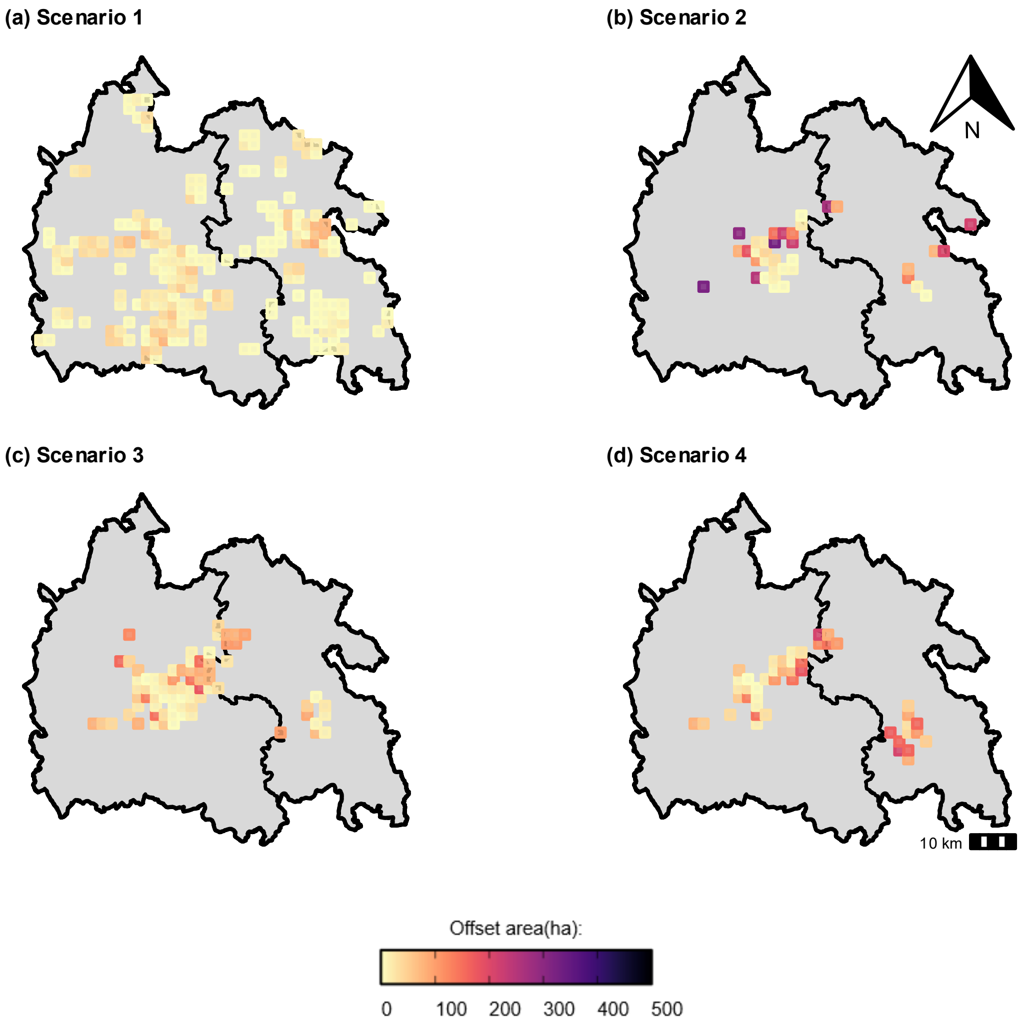

Figure 2: Comparison of the spatial distribution of Biodiversity Net Gain (BNG) offset sites within the region (Oxfordshire and Buckinghamshire) under four scenarios; (a) Scenario 1 - Closest offset, (b) Scenario 2 - Local offset, (c) Scenario 3 - Local offset to support conservation priorities, and (d) Scenario 4 - Regional offset to support conservation priorities. Onsite offsets are the same for all four scenarios, while the location of off-site offsets varies between the four scenarios.

3.2. Scenario costs and benefits

3.2.1. Species Richness

Figure 3 illustrates the relative performance of the four scenarios on six dimensions. All scenarios resulted in biodiversity improvements, with increases in species richness ranging between 7% and 12%. The lowest increase is attributed to Scenario 1 where offsets were located closest to the development. Scenarios 2 and 3 resulted in very similar gains in species richness (approximately 9%). In both scenarios offsets were constrained to the development's LPA, therefore the added constraint of the NRN in Scenario 3 had minimal effect on our proxy measure of biodiversity. However, there is a notable increase in species richness gain, to 12%, when removing the LPA constraint in Scenario 4. This prioritises the region's NRN, resulting in the greatest biodiversity improvement of all four scenarios.

3.2.2. Opportunity Cost of agriculture

Scenario 2 had the lowest opportunity cost out of the four scenarios, approximately £33.51 million (Figure 3b). This is not unexpected; Scenario 2 involved prioritising placing offsets on the lowest cost areas whereas Scenarios 3 and 4 prioritised different values (contribution to the NRN). The offset sites in Scenario 2 were concentrated in the centre of the region where the value of agricultural land was lowest (Figure 3b). As expected, Scenario 1 had the highest cost of all scenarios (£37.94 million) because the prioritisation did not incorporate cost.

3.2.3. Carbon sequestration

There was limited variation in the scenarios' estimated carbon sequestration values (Figure 3c). This is expected because the scenarios assumed the same area of woodland planted to create the BNG offsets (approximately 34.5 km^2).

3.2.4. Flood damage avoided costs

Scenario 4 resulted in the lowest avoided cost of flooding (~£7.03 million), whereas Scenario 3 resulted in the highest avoided cost (~£8.58 million). Scenario 1, which distributed offsets more widely across the region (Figure 3a), followed closely with a total avoided cost of £8.17 million. These differences are likely to be related to the particularities of the geography of the study region rather than the criteria in the scenarios themselves.

3.2.5. Public Greenspace access

Access to public greenspace was already high across the region before the offsets (98.97% of Output Areas, *n* = 3,832). The addition of BNG offsets increased access for all scenarios. Scenario 3 resulted in the highest increase in public greenspace access with 3,842 Output Areas (99.23%) having access after the implementation of the BNG sites. Despite differences in their BNG site distributions (Figure 3a), Scenarios 1 and 2 resulted in the same increase in access; 3,838 Output Areas (99.12%) having access after the implementation of the BNG sites.

3.2.6. Total monetary benefits

The monetisable elements of this framework (i.e., opportunity cost of agriculture, flood damage avoided costs, and carbon sequestration) were combined to give a partial monetary value for each scenario (Figure 3e). Overall, Scenarios 2 and 3 (the two local offset scenarios) resulted in the highest monetary value (-£9.56 million), Scenario 1 (closest offsets) had the lowest monetary value (-£13.57 million), with Scenario 4 (regional, conservation-prioritising) in the middle.

Overall, the main pattern seen in the total monetary value, of Scenario 1 being clearly less good than the other three scenarios, is consistent across the board, with a trade-off being seen between Scenario 4 being substantially better for biodiversity and slightly less good as regards total monetary value, than scenarios 2 and 3 (Figure 3).

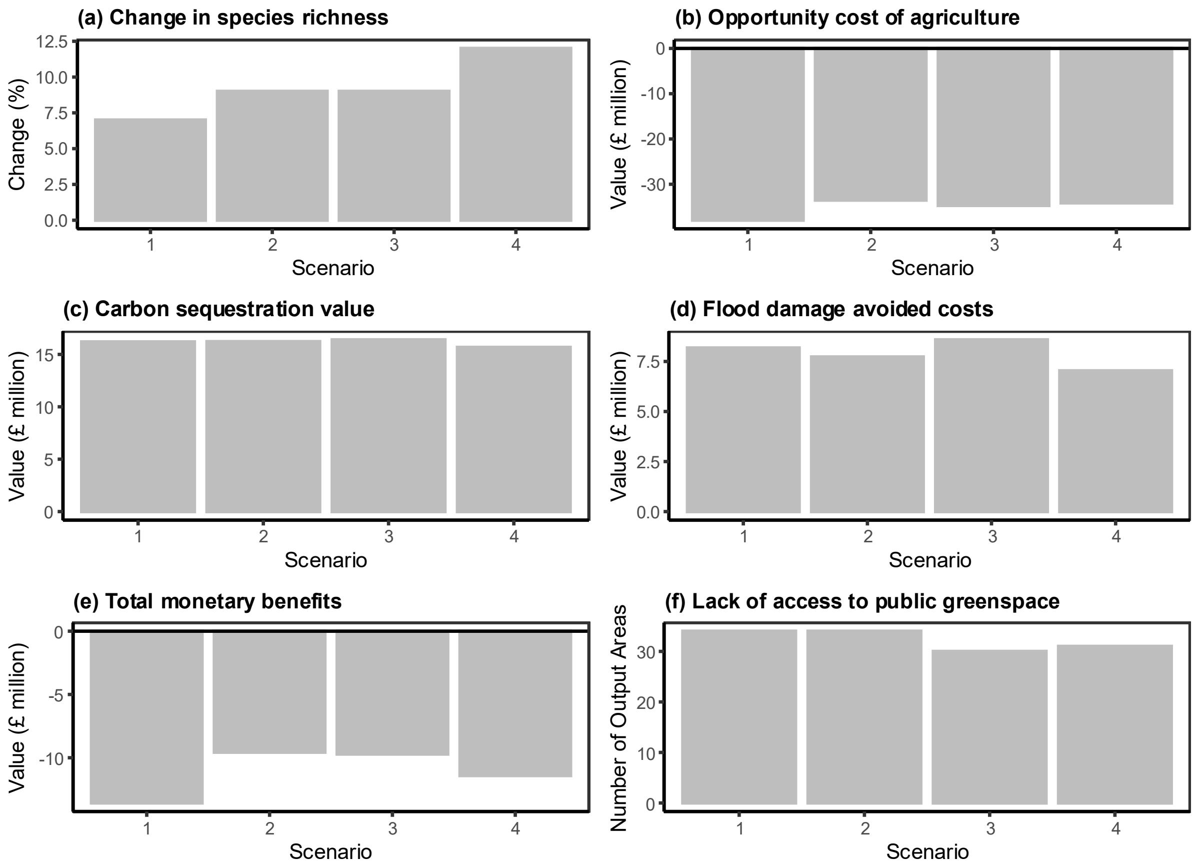

Figure 3: Estimated benefits associated with four scenarios for Biodiversity Net Gain (BNG) within the region (Oxfordshire and Buckinghamshire): Scenario 1 - Closest offset, Scenario 2 - Local offset, Scenario 3 - Local offset to support conservation priorities, and Scenario 4 - Regional offset to support conservation priorities. Benefits quantified include: (a) percentage change in species richness (for species of conservation priority), (b) opportunity cost of agriculture, (c) carbon sequestration value, (d) flood damage avoided costs, (e) total monetary benefits (b + c + d), and (f) lack of access to public greenspace. Associated values are presented in the Supplementary Information (SI 3).

4. Discussion

In this study we developed a novel and generalisable framework for quantitatively synthesising and comparing options for implementing a biodiversity net gain policy at the regional level, the scale at which infrastructure planning decisions are generally made. We applied this framework to assessing the effectiveness of operationalising the national BNG policy in England, a policy which is attracting a lot of interest worldwide. We modelled the impact of realistic scenarios of spatial allocation of BNG at a regional scale on biodiversity (species richness), and ecosystem service co-benefits. Our framework enables the quantification of the scenarios' associated costs and benefits within a real landscape, thereby identifying potential opportunities for policy integration and/or trade-offs between policies and priorities.

Within our case study, we explored the potential effect of aligning BNG with nature recovery networks, a central component of the UK's (England, Scotland, Wales and Northern Ireland) government's "apex" goal to improve the state of nature (Department for Environment, Food and Rural Affairs, 2023a). Scenario 4 results revealed that this integrated approach could benefit regional biodiversity more than the other three scenarios (species richness increase of 12%, Figure 3). This was not an unexpected result because the NRN is based on prioritising areas where the prospects for nature recovery are good (Smith et al., 2022).

BNG aims to compensate for lost biodiversity, and thus cannot in itself produce nature recovery, as required by national biodiversity targets. Therefore it must be additional to other actions within a wider conservation strategy, such as improving the extent and condition of protected areas. Nonetheless, compensation for biodiversity losses from development cannot occur in isolation from wider conservation strategies (Simmonds et al., 2020). These results suggest that in England, effectively designed NRNs could provide a useful framework for LPAs to prioritise and assign the locations for offsite offsets (Smith et al., 2022). Similar recommendations have been made in regions of the USA (Kiesecker et al., 2009) and Australia (Kujala et al., 2015). Both studies applied principles of systematic conservation planning to identify priority areas for biodiversity offsets. With a long history in South Africa (Botts et al., 2020), systematic conservation planning is now increasingly recognised as a key foundation for integrated and spatially explicit land-use planning. Therefore, using systematic conservation planning to inform the location of offsets may be one way to mitigate some of the potential risks and unintended consequences of "flexible" offsetting highlighted by Bull et al. (2015).

We estimated the potential benefits of integrating the placement of offsite BNG sites alongside the NRN in Scenarios 3 and 4. However, we did not extend our analysis to include Local Nature Recovery Strategies (LNRSs), as these are still under development across England and were unavailable for spatial modelling at the time of analysis. In England, LNRSs are intended to establish agreed priorities for nature recovery by working with interested parties to map actions with the greatest environmental benefit (Department for Environment, Food & Rural Affairs & Natural England, 2024). This approach uses similar steps to those that underpin systematic conservation planning (Department for Environment, Food & Rural Affairs, 2023b) and is consistent with how the proposed NRN for the region was created, focusing on the same priority habitats (Smith et al., 2022). Proposed changes to the BNG regulations (currently under consultation) present the option to use LNRSs alongside National Character Areas within the Metric's spatial risk multiplier, in place of LPAs (Department for Environment Food & Rural Affairs, 2025) — potentially unlocking broader opportunities for offsite offsets. If we provisionally draw parallels between the LNRS and the NRN used in this study, we observe that prioritising the placement of offset sites within the NRN (Scenario 4) resulted in the highest benefits to species richness (Figure 3a). In comparison, Scenario

3 prioritised offsets according to the NRN, but restricted them to the same LPA as the development. Scenario 3 still performed well across the quantified costs and benefits (Figure 3).

To ensure an uplift in biodiversity, as is expected from the implementation of BNG, we assumed a 1:1 ratio of land converted for development and land set aside for offset. We recognise that this is not a realistic assumption as metric units can be delivered via higher condition habitats within a smaller footprint. Previous studies of BNG in England have found this to be the more common approach to offsetting with, on average, areas of open greenspace decreasing by 30% as a result of development and associated BNG compensation (zu Ermgassen et al., 2021). However, the broad habitat classifications inputted into this modelling system are unable to account for improvements in habitat quality and were unable to evaluate the benefits and costs associated with more distinctive habitats and improving habitat distinctiveness and conditions (McVittie & Faccioli, 2020). In addition, our models do not consider the delay between habitat loss and creation, which is also an issue for BNG as currently implemented (zu Ermgassen et al., 2021). However, these caveats do not affect the relative performance of the scenarios in terms of benefits and costs. This study does not intend to be an accurate model of what will happen in the specific region with the integration of BNG, but a demonstration of how different scenarios of BNG implementation could play out at a regional level, resulting in costs and benefits to people and biodiversity. In addition, we took the distribution and quantity of housing to be an externally determined variable. This was justified as it was based on local housing plans. However, a truly integrated approach to spatial planning that explored the trade-offs involved in meeting the constraints imposed by a range of different national priorities (e.g. housing, renewable energy, nature restoration, infrastructure, agriculture) would not necessarily take the proposed housing plan as a given. Other options for housing provision that are more aligned with other government priorities could then be explored (zu Ermgassen et al., 2022).

Scenario 1, whereby offset sites are placed in closest proximity to the development, has the lowest total monetisable benefits and the lowest potential for biodiversity uplift (Figure 3). As such, if the location of offsite offsets were determined in this way, it may be seen as an inefficient use of resources to compensate for biodiversity losses from development. However, our regional modelling does not capture site-specific considerations; it is feasible that local sites can provide for biodiversity and other co-benefits (Atkins et al., 2025). Another justification given for the close proximity of offsets is to ensure local people, who are losing their natural spaces to development, are compensated (Jones et al., 2019; Moreno-Mateos et al., 2015; Tupala et al., 2022). However, a recent choice experiment of hypothetical BNG projects revealed that public access and species richness were proportionally more important than proximity to the development (Butler et al., 2025). In this study, we assumed a combination of onsite and offsite offsets, and assumed that both types were publicly accessible. Therefore we did not observe any loss in access to public greenspace. However, in practice, this may not be the case; although, in England, it appears one intention of BNG is to contribute to improved greenspace access (Department for Environment Food and Rural Affairs, 2023a), there are no legal requirements for LPAs to ensure this is the case in the planning process. Consequently, there is a risk of BNG creating or enhancing natural areas without public access. This may narrow the range of beneficiaries – if onsite, to those living in the new development and if offsite, to the owners of the enhanced land, whilst excluding those who have experienced the loss of nature (Bateman & Zonneveld, 2019). In this particular region, where baseline levels of greenspace access are high, we estimated approximately 98.97% of Output Areas in the region are within 15-min walking distance of greenspace. Nationally, only 38% of people have access to greenspace within 15 minutes of their homes (Department for Environment Food and Rural Affairs, 2023a). Therefore, it could be argued that the restrictions in access to greenspaces is less of a concern for LPAs in this particular context. However, this stance neglects to acknowledge the importance of the intrinsic attachment people have to their local green spaces (Jones et al., 2019; Moreno-Mateos et al., 2015; Tupala et al., 2022) and the socio-economic disparities between those who have access to nature and greenspace and those who do not. Ensuring access to good quality greenspace as a priority for BNG offsets could help to address issues of social disparities (Lovell et al., 2020; Public Health England, 2020) and associated physical and mental health benefits (for reviews see; Gascon et al., 2015; Hartig et al., 2014).

While our scenarios show only modest differences in offset placement (Figure 2) and estimated benefits (Figure 3)—particularly in Scenarios 2 and 3—one of the core contributions of this work lies in the development of a systematic framework (Figure 1) for evaluating biodiversity offsetting under varying local constraints and priorities. The results are specific to one region in England (Buckinghamshire and Oxfordshire) and reflect a set of assumptions that were co-developed with the authors and interested parties involved in biodiversity net gain (BNG) policy and implementation relevant to this region. This collaborative scenario design is a key strength of the analysis. In this region, outcome variation was limited due to relatively uniform agricultural opportunity costs, high existing greenspace access, and carbon sequestration potential being largely predetermined by woodland cover assumptions. Flood damage avoidance was similarly constrained, driven more by the density of housing and associated property values. These factors may differ substantially in other regions. For instance, in areas with less agricultural land or lower greenspace access, we might observe more pronounced impacts from offset placement decisions. We acknowledge that the regional scale used here, while appropriate for housing development decision-making in England, may not be optimal for maximising benefits to biodiversity and other ecosystem services, or for minimising opportunity costs to agriculture. Expanding the analysis to a broader scale (e.g., national level) could result in greater gains in biodiversity and ecosystem services (Mancini et al., 2025). Although our case study is region-specific, the framework (Figure 1) is designed to be transferable. It provides a structured method for comparing BNG placement strategies, enabling more strategic and locally responsive offsetting decisions across different contexts.

5. Conclusion

BNG is designed as a scheme to compensate for biodiversity loss from development by uplifting biodiversity both onsite and offsite. Our results suggest that to maximise gains in species richness, the placement of offsite BNG offsets should be integrated with regional biodiversity conservation strategies such as NRNs (i.e., Scenario 4). This approach coincides with potentially greater benefits from other ES and reduced opportunity costs compared to a policy of keeping offsets as close as possible to development sites. To ensure that these benefits transpire, efforts need to be made to ensure that suitably designed NRNs have been established, with agreed priorities for nature recovery based on consultation with interested parties; systematic conservation planning is one mechanism to ensure this. However, such spatial prioritisation does not necessarily justify the loss of nature to the residents of one area to improve nature in another. We therefore also tested restricting offsite BNG to supporting conservation priorities within the same LPA as the housing development (Scenario 3). This performed comparatively well. Although our model was implemented in a specific regional context, to align with the scale at which real-world decisions are made, our framework for exploring spatial priorities for BNG-associated offsets and the associated trade-offs is broadly generalisable. Applying this approach in other areas (for example more urbanised areas where access to green space and to suitable land for offsetting may be more limited) could highlight how trade-offs play off in different situations.

Acknowledgments/Funding

Supported by Natural Environment Research Council (NERC), grant number NE/W004976/1, as part of the Agile Initiative at the Oxford Martin School. We would like to directly thank all members of the core project team who supported this project: Prue Addison (Berkshire, Buckinghamshire and Oxfordshire Wildlife Trust); Julia Baker (Mott MacDonald); Hannah Nicholas; Michael Clark; Richard Grenyer; Cecilia Larrosa; Owen Lewis; Vidya Narayanan; Joss Wright.

Author contributions

The idea for the analysis was conceived by FE, IJB, MCM, and RMC. Scenarios were developed in collaboration with all authors. Analyses were undertaken by MCM and RMC. This paper was written in collaboration with all authors.

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Supplementary Information (SI)

1. The Region's local plan details

The expected number (n = 314) and location of the future developments were taken from the Local Plan data for Buckinghamshire and Oxfordshire. The Local Plans were prepared by the LPAs to guide development within Buckinghamshire and Oxfordshire ranging between 2011 and 2031. The location of all included developments are shown in Figure SI1.1.

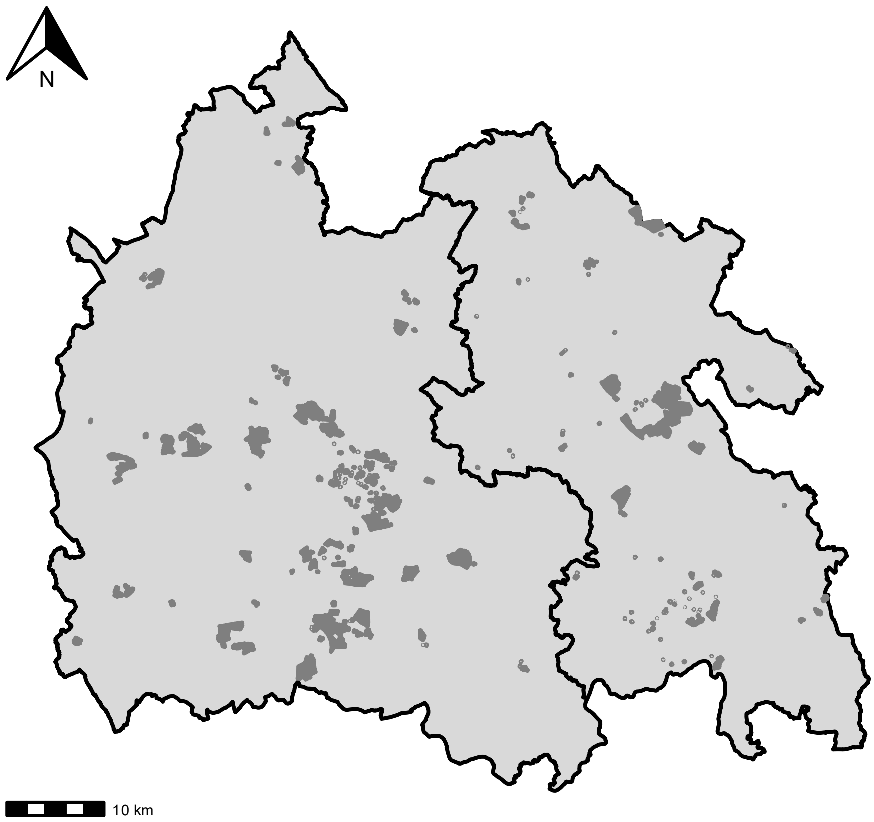

Figure SI1.1: Location of developments according to Local Plan data for Buckinghamshire and Oxfordshire

2. Modelling species richness

We followed the methods in Mancini et al., (2024) to assess the impact of offset site placement across the different scenarios. The Joint Nature Conservation Committee (JNCC) biodiversity modelling framework was applied, which follows Croft et al. (2017). While the full framework encompasses nearly 1,000 species, a subset of 100 UK conservation priority species was selected for this analysis. A full list of the selected species is provided in Table S12.1.

Table SI2.1: List of species of conservation priority within the UK included in the biodiversity model.

Taxonomic group	**Species**	**English common name**
Bird	*Acanthis cabaret*	Lesser Redpoll
Bird	*Alauda arvensis*	Skylark
Bird	*Anthus trivialis*	Tree Pipit
Bird	*Botaurus stellaris*	Bittern
Bird	*Caprimulgus europaeus*	Nightjar
Bird	*Emberiza citronella*	Yellowhammer
Bird	*Emberiza schoeniclus*	Reed Bunting
Bird	*Locustella naevia*	Grasshopper Warbler
Bird	*Lullula arborea*	Woodlark
Bird	*Motacilla flava subsp. flavissima*	Yellow Wagtail
Bird	*Muscicapa striata*	Spotted Flycatcher
Bird	*Numenius arquata*	Curlew
Bird	*Perdix perdix*	Grey Partridge
Bird	*Phylloscopus sibilatrix*	Wood Warbler
Bird	*Streptopelia turtur*	Turtle Dove
Bird	*Turdus torquatus*	Ring Ouzel
Bird	*Vanellus vanellus*	Lapwing
Herptile	*Vipera berus*	Adder
Invertebrate – bee	*Bombus monticola*	Mountain Bumblebee
Invertebrate – beetle	*Cercyon convexiusculus*	Water Beetle sp.
Invertebrate – beetle	*Gnorimus nobilis*	Noble Chafer
Invertebrate – beetle	*Liopterus haemorrhoidalis*	Water Beetle sp.
Invertebrate – beetle	*Lucanus cervus*	Stag Beetle
Invertebrate – butterfly	*Boloria selene*	Small Pearl-Bordered Fritillary
Invertebrate – butterfly	*Coenonympha pamphilus*	Small Heath
Invertebrate – butterfly	*Coenonympha tullia*	Large Heath
Invertebrate – butterfly	*Cupido minimus*	Small Blue
Invertebrate – butterfly	*Erebia epiphron*	Mountain Ringlet
Invertebrate – butterfly	*Erynnis tages*	Dingy Skipper
Invertebrate – butterfly	*Hipparchia Semele*	Grayling
Invertebrate – butterfly	*Lasiommata megera*	Wall
Invertebrate – butterfly	*Limenitis camilla*	White Admiral
Invertebrate – butterfly	*Satyrium w-album*	White-Letter Hairstreak
Invertebrate – cricket	*Leptophyes punctatissima*	Speckled Bush Cricket
Invertebrate – cricket	*Metrioptera brachyptera*	Bog Bush Cricket
Invertebrate – moth	*Cossus cossus*	Goat Moth
Invertebrate – moth	*Acronicta psi*	Grey Dagger
Invertebrate – moth	*Allophyes oxyacanthae*	Green-brindled Crescent
Invertebrate – moth	*Dasypolia temple*	Brindled Ochre
Invertebrate – moth	*Xanthorhoe decoloraria*	Red Carpet

Invertebrate – snail	*Cochlodina laminata*	Plaited Door Snail
Invertebrate – snail	*Monacha cantiana*	Kentish Snail
Invertebrate – snail	*Zonitoides excavatus*	Hollowed Glass Snail
Lichen	*Anaptychia ciliaris ciliaris*	Lichen subsp.
Lichen	*Leptogium brebissonii*	Lichen sp.
Lichen	*Parmeliella testacea*	Lichen sp.
Lichen	*Pseudocyphellaria intricata*	Lichen sp.
Lichen	*Usnea articulata*	String-Of-Sausage Lichen
Mammal	*Barbastella barbastellus*	Barbastelle bat
Mammal	*Felis silvestris*	Wildcat
Mammal	*Lepus europaeus*	European hare
Mammal	*Lepus timidus*	Mountain Hare
Mammal	*Martes martes*	Pine Marten
Mammal	*Micromys minutus*	Harvest Mouse
Mammal	*Muscardinus avellanarius*	Hazel Dormouse
Mammal	*Mustela putorius*	Polecat
Mammal	*Myotis bechsteinii*	Bechstein’s bat
Mammal	*Nyctalus noctula*	Noctule Bat
Mammal	*Plecotus auritus*	Brown Long-eared Bat
Mammal	*Rhinolophus ferrumequinum*	Greater Horseshoe Bat
Mammal	*Rhinolophus hipposideros*	Lesser Horseshoe Bat
Mammal	*Sciurus vulgaris*	Eurasian red squirrel
Vascular plant	*Anchusa arvensis*	Field bugloss
Vascular plant	*Andromeda polifolia*	Bog Rosemary
Vascular plant	*Arctostaphylos alpinus*	Mountain bearberry
Vascular plant	*Asplenium viride*	Green spleenwort
Vascular plant	*Atriplex laciniata*	Frosted Orache
Vascular plant	*Blysmus rufus*	Saltmarsh Flat-Sedge
Vascular plant	*Cakile maritima*	Sea Rocket
Vascular plant	*Campanula glomerata*	Clustered Bellflower
Vascular plant	*Carex extensa*	Long-Bracted Sedge
Vascular plant	*Carex magellanica*	Tall Bog-Sedge
Vascular plant	*Centaurium pulchellum*	Lesser Centaury
Vascular plant	*Cerastium arvense*	Field Mouse-Ear
Vascular plant	*Cirsium eriophorum*	Woolly Thistle
Vascular plant	*Daphne laureola*	Spurge-Laurel
Vascular plant	*Eriophorum latifolium*	Broad-Leaved Cottongrass
Vascular plant	*Fumaria muralis*	Common Ramping-Fumitory
Vascular plant	*Genista anglica*	Petty Whin
Vascular plant	*Genista tinctoria*	Dyer’s Greenweed
Vascular plant	*Gnaphalium supinum*	Dwarf Cudweed
Vascular plant	*Goodyera repens*	Creeping Lady’s-Tresses
Vascular plant	*Hypericum elodes*	Marsh St John’s-Wort
Vascular plant	*Lamium hybridum*	Cut-Leaved Dead-Nettle
Vascular plant	*Leymus arenarius*	Lyme Grass
Vascular plant	*Lycopodium clavatum*	Stag’s-Horn Clubmoss
Vascular plant	*Neottia nidus-avis*	Bird’s-Nest Orchid
Vascular plant	*Ornithopus perpusillus*	Bird’s-Foot
Vascular plant	*Orthilia secunda*	Serrated Wintergreen
Vascular plant	*Oxyria digyna*	Mountain Sorrel

Vascular plant	*Pyrola media*	Intermediate Wintergreen
Vascular plant	*Radiola linoides*	Allseed
Vascular plant	*Ranunculus omiophyllus*	Round-Leaved Crowfoot
Vascular plant	*Saxifraga tridactylites*	Rue-Leaved Saxifrage
Vascular plant	*Silaum silaus*	Pepper-Saxifrage
Vascular plant	*Thymus pulegioides*	Large Thyme
Vascular plant	*Tilia cordata*	Small-Leaved Lime
Vascular plant	*Trifolium fragiferum*	Strawberry Clover
Vascular plant	*Trifolium striatum*	Knotted Clover
Vascular plant	*Vaccinium microcarpum*	Small Cranberry

3. Supplementary results – estimated benefits

Table SI3.1: Estimated benefits for four scenarios for Biodiversity Net Gain (BNG) within the region (Oxfordshire and Buckinghamshire)

Benefit	Scenario 1 – Closest offset	Scenario 2 – Local offset	Scenario 3 – Local offset to support conservation priorities	Scenario 4 – Regional offset to support conservation priorities
Increase in species richness (%)	7%	9%	9%	12%
Cost (£)	£37,942,047.17	£33,507,953.07	£34,685,489.45	£34,114,674.76
Carbon sequestration (£)	£16,194,679.73	£16,219,700.90	£16,393,882.68	£15,672,765.48
Flood damage avoided costs (£)	£8,173,567.04	£7,724,929.54	£8,581,109.67	£7,032,900.74
Output Areas with access to public greenspace within 1km (%)	99.12%	99.12%	99.23%	99.20%