**Biodiversity offsets must address the trade-offs between people and nature:**

**Case study and general principles**

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**SUMMARY**

A basic requirement for global sustainability is to halt the ongoing decline in biodiversity and wider ecosystem services, yet infrastructure developments such as new housing inevitably cause environmental impacts. To counteract this, developers are increasingly required to resource projects which offset those impacts, delivering biodiversity or wider environmental net gains1. However, analysis of offsets in England to date show that the large majority are conducted within development sites rather than being targeted towards far better opportunities for net gain of either biodiversity or ecosystem services elsewhere2. Here we compare current and alternative approaches to offsetting considering the biodiversity gains, ecosystem service co-benefits and economic costs they generate. Our results confirm that while current practice is better than nothing, it performs relatively poorly across all criteria. Analysis shows that by incorporating ecological and economic information into the targeting of offsets they can provide a significant contribution to addressing the challenge of biodiversity loss or deliver substantial ecosystem service co-benefits to disadvantaged communities. The analytical methods and results presented here could support a substantial improvement in the operation and outcomes of biodiversity offsetting globally.

# **INTRODUCTION**

Adequate housing is a basic human right3,4, and under the Sustainable Development Goals (SDGs) there is an international commitment to expand built infrastructure (SDG 9)3. However, this sets up a potential conflict with the simultaneous commitment to end biodiversity loss (SDG 15)3. The recent UN Convention on Biological Diversity (CBD) Post-2020 Global Biodiversity Framework5 requires signatory countries to halt and reverse the loss of biodiversity by 2030. Given the need for both new infrastructure and conservation enhancement, "net" biodiversity gain policies have gained attention6. These aim to limit the negative environmental impacts of development on a site, while allowing some loss of biodiversity compensated for by offsets (biodiversity enhancements) elsewhere. One such policy is ‘Biodiversity Net Gain’ (BNG)7 which has gained attention as a way to limit the net negative environmental impacts of development1. Under BNG principles biodiversity losses from development need to be more than offset by improvements elsewhere7-10. Biodiversity net-gain policies have become widely embedded in both national and international policy discourse, as well as in business and finance1,8,11-13. For example, England’s 2021 Environment Act mandates that, for planning permission to be granted, all developments are required to deliver BNG with a minimum uplift in biodiversity of 10%14. This policy has few exceptions, is considered an important contribution towards halting further biodiversity loss15, and has been internationally acclaimed by some as “the most ambitious biodiversity policy in the world”16.

While the BNG principle has been well received, it is its mode of implementation which will determine the practical effectiveness of the policy. Spatial targeting of offsets is particularly important, as the effectiveness of management interventions to improve biodiversity and natural capital landscapes is context dependent17. However, many land use policies (for example agricultural subsidies18,19) are applied at uniform rates across all areas irrespective of the fact that the natural and human environment and corresponding benefits of change vary vastly between locations. This means that, at best, the limited funds available for environmental improvement are allocated inefficiently delivering poorer outcomes, while at worst this approach encourages the wrong activities in the wrong places (for example, planting trees on high carbon soils leading to net increase in greenhouse gas emissions20). Quite obviously the spatial targeting of BNG to places which are poor for biodiversity will do little to bend the curve on biodiversity loss21. Similarly, if we are interested in enhancing access to high quality environments for disadvantaged groups then an implementation mechanism that targets BNG offsets in order to minimise their cost or ties them to the sites of infrastructure development is unlikely to provide high value for money in terms of addressing inequality. As such, land use policy and its implementation should not implicitly treat the natural environment as homogeneous, but rather should incorporate environmental and social variability into both the formulation and implementation of policy.

While net gain for biodiversity is the key stated motivator for, current guidance for BNG in England consider the issue of where offsets should be located through an explicit policy objective to be ‘of clear benefit to people and local communities’22. Indeed, the BNG ‘spatial hierarchy’ adopted does not target either biodiversity or disadvantaged groups, instead simply preferring on-site or near-site offsets to more distant off-site compensation23-25. Given this, a key goal for our case study is to understand the degree to which the adopted spatial hierarchy delivers against biodiversity and social equity goals. While our case study considers BNG in England, the general nature of spatial dependency in landscapes means our findings have wider relevance17,26.

The current BNG ‘spatial hierarchy’ is further incorporated into a ‘mitigation hierarchy’9,27 where, once opportunities for avoiding damage are exhausted15, on-site or near-site offsets are given precedence over more distant options. The explicit bias towards on-site and near-site offsets is incorporated as a ‘Spatial Risk Multiplier’ within England’s Biodiversity Metric28, a habitat-based assessment tool developed to estimate pre- and post-development biodiversity. The inclusion of the ‘Spatial Risk Multiplier’ systematically reduces the ‘biodiversity value’ of offset sites located outside the development’s local planning authority28 so that a more substantial improvement occurring at distance from the development site can be accorded a lower value than a smaller improvement near to that development. Higher weighting of local offsets is further supported within the National Planning Policy Framework25. Unsurprisingly, analysis of early adopters of BNG show that the majority of offsetting sites are typically located within or near to development sites2.

While local offsetting is administratively straightforward, it gives local planners additional incentives to permit more development as BNG benefits are captured locally, which may of itself have undesirable impacts if biodiversity offsets are inadequate. This aside, from an ecological perspective the current approach to BNG is difficult to defend. Proximity in itself does not ensure fungibility as offsets are by definition substitutes for the original habitat. The ‘ecological equivalence’ of offsets is evaluated according to a metric which reflects a hierarchy of values set by institutional perceptions of stakeholder preferences regarding the aspects of nature to be prioritised12,29 rather than solely conservation priorities. An emphasis on proximity may result in inefficient outcomes for conservation at a national scale, thus wasting resources which could be targeted to generate far greater biodiversity improvements. Perhaps most importantly, the bias towards local offsetting ignores the well-established need to restore coherent national networks of conservation habitats30 and address the central problem of biodiversity loss31,32.

From a social perspective, the local focus also disregards national concerns over recreational access to nature. The UK’s National Planning Policy Framework25 specifies that “opportunities to improve biodiversity in and around developments should be integrated as part of their design, especially where this can secure measurable net gains for biodiversity or enhance public access to nature where this is appropriate” (p.52 para. 180). However, this specification limits considerations of access to the development site and does not consider wider socio-economic inequalities associated with greenspace access in England33. Consequently, the local approach may be unfair to disadvantaged groups currently suffering the most degraded environments34, doing nothing for problems of poor wellbeing, health care needs, and lower overall life expectancy35-37. Such neighbourhoods are typically unattractive for developers and therefore unlikely to benefit from BNG policies biased towards offsets near to developments.

More generally, any offsetting strategy needs to explicitly acknowledge that trade-offs are an inherent feature of land management, involving not only conservation objectives, but also human livelihoods and wellbeing38-45. Further, evidence shows that localised mitigation activities often result in highly dispersed conservation projects that generate limited ecological benefits but impose substantial oversight burden on the regulatory community46. In contrast, landscape and national scale planning with a habitat network perspective (e.g. providing effective linkage between existing, fragmented conservation habitats) is both more cost-effective and more ecologically effective for promoting biodiversity gains30,46.

As a local approach is no guarantee of win-win outcomes from BNG offsetting, in this paper we demonstrate the potential for improvements arising from removing the current bias in favour of local offsets. To do so we use existing models of biodiversity and ecosystem services47,48 to: quantify species richness for a set of species of conservation priority48 (details in Methods §3 and Supplementary Information (SI) §SI-3); assess recreational access co-benefits47 (Methods §5, §SI-5); and calculate the costs of offsetting (the major element of which is the compensation farmers and landowners require for land use change (Methods §4, §SI-4)47. These models are applied across England to five scenarios, each examining a different rule for BNG offsetting (Methods §7, §SI-7): (1) Local offsetting (the status quo); (2) Maximise conservation benefits; (3) Minimise costs; (4) Maximise co-benefits (access) minus costs; (5) Maximise equity weighted co-benefits. Table 1 details the rules used in each scenario.

Table 1: Biodiversity Net Gain (BNG) offset scenarios and corresponding rules for the selection of offset sites.

|  |  |
| --- | --- |
| Offset scenario | Rules for selecting offset site |
| (1) Local offset (status quo) | Offset within or adjacent to construction/infrastructure site (current practice). |
| (2) Maximise conservation benefits | Offset where the highest improvements for a set of species of conservation priority can be achieved.  |
| (3) Minimise costs | Offset where the major costs of offsetting (compensation to landowners) are minimised.  |
| (4) Maximise access co- benefits minus costs | Offset where the sum of the monetised co-benefits of offsetting (access for recreation) minus the offsetting cost is maximised.  |
| (5) Maximise equity weighted access co-benefits | Using HM Government allowances49 giving higher weights to the co-benefits received by those with lower incomes.  |

To clearly demonstrate the different consequences of these approaches to offsetting, each of the rules given in Table 1 were applied to estimates of housing developments across England over a 25 year period50 (Methods §2, §SI-2). We assessed expected change in species richness51 for a set of 100 species of conservation priority, the value of recreational access co-benefits (assessed using standard economic techniques) and the expected costs of the scheme (compensation to landowners). Following the common practices of offsetting to date52, we assume that offset areas are of the same size as development areas. Offsets were modelled as the conversion of agricultural farmland to semi-natural grassland, both the most common habitat type delivered through BNG so far53, and an outcome land use applicable throughout the study area. This ensured that assessments were determined by biodiversity, co-benefit and cost outcomes alone and not influenced by variation in the offset habitat type. Optimisation according to each of the offset rules used in each scenario was achieved using the NEV decision support system47,54 (which underpinned the UK National Ecosystem Assessment55,56; further details on which, along with additional information on each scenario, are provided in Methods and SI). Using these scenarios we show that removing the current bias towards local offsetting and instead targeting offsets according to expected outcomes can provide superior improvements in biodiversity, cost-effectiveness, and equity.

# **RESULTS**

## Just over 300,000 hectares of farmland are expected to be lost to development across England over the 25 year analysis period. This area was allocated via each of the five scenarios shown in Table 1 and the differing rules for each were applied to generate the offset locations shown in **Figure 1(a)**. As can immediately be seen, changing offset rules radically alters offsetting locations. While the (1) current bias towards development sites skews offsets to the environs of major cities (the ring of offsets around London is particularly prominent), (2) maximising conservation priority radically alters this by favouring locations where species of conservation concern would benefit most from offsetting. Minimising costs (3) moves offsets away from prime value farmland in the east of the country, a pattern echoed in the maximisation of access co-benefits minus those costs (4). In comparison to the latter, the weighting of access co-benefits towards disadvantaged communities (5) shifts offset locations away from the generally affluent south-east of England.

INSERT FIGURE 1 ABOUT HERE

The radar chart **Fig.1(b)** compares all five offset scenarios. Here the closer to the edge of the chart the more a scenario delivers against the goals set at each compass point. Perhaps most noticeable is the poor performance of the current implementation of BNG (Scenario (1); shown in black) across all criteria. This approach is outperformed on all criteria by other rules (e.g. Scenario (4) the maximisation of co-benefits minus costs dominates current implementation on all counts). Removing the bias towards local implementation and allowing offsets in locations which are best for biodiversity (Scenario (2)) produces much better outcomes for species of conservation concern (i.e. BNG focussed on biodiversity rather than largely human preferences) than current implementation although at the cost of poor performance across other criteria.

Details of these measures for all scenarios are given in the histograms of **Fig.1(c)**. While the current practice of Scenario (1) performs relatively poorly against the central stated aim of the BNG policy, Scenario (2) doubles the conservation gains achieved by local offsetting, although it performs poorly against other criteria. Similarly, Scenario (3), which locates offsets so as to minimise costs, also performs poorly against other criteria although it still outperforms the status quo in terms of its net co-benefits minus costs. The latter measure is maximised by Scenario (4) which also performs well against all other criteria except conservation improvements (although even here it marginally outperforms the status quo). In comparison to this, Scenario (5) trades-off to varying degrees across criteria while delivering the best outcomes in terms of equity weighted co-benefits for disadvantaged communities. It is worth noting that while Scenario (2) maximises conservation gains, it performs the worst when it comes to equity-weighted benefits from accessing nature. Equally, while Scenario (5) maximises equity-weighted benefits from accessing nature, it yields the lowest levels of biodiversity improvements for species of conservation priority, illustrating the existing trade-offs between improving biodiversity and making nature accessible even before the influence of human disturbance on biodiversity is accounted for.

Finally, **Fig.1(c)(iv)** reveals that, in purely monetary terms, all scenarios generate net costs. This shows that protecting biodiversity is not a cost-free undertaking, with the current approach delivering the second highest net costs.

# **DISCUSSION**

Our findings prompt a number of conclusions, the first being that in our modelling framework the current practice of encouraging local offsetting delivers relatively poor biodiversity gains at high costs and with low co-benefits. If the commonly adopted practice of local offsetting continues2, it may result in highly inefficient use of resources to deliver suboptimal biodiversity gains.

Addressing biodiversity loss requires a coordinated approach and constraining offsets to the proximity of development sites does not support the widely recognised need to embed biodiversity policies within a coherent conservation network30. While some defend local offsets as more likely to deliver like-for-like ecological equivalence57 the very concept of offsetting embodies the idea of some form of trade between surrogates. ‘In-kind’ considerations assume substitutability of ecological communities and the outcomes depend on the specific metric adopted12,27 (note that the Convention on Biological Diversity definition of biodiversity excludes the notion of an ecologically equivalent offset).

BNG offsets are (at least in name) supposed to benefit species of conservation concern but one anthropocentric argument for local offsetting might be that it compensates those who have lost out from development via reduced opportunities for recreation and associated health benefits10,58. However, one case study assessment demonstrates the risk that, instead of being designed to benefit those who have suffered losses from the development (i.e. those who lived in the area previously and used that site for access to nature), offsets are located to the best advantage of those living in the new homes created by the developer, with houses nearest to such offsets being sold at a premium34. By building on greenspace, we necessarily see access worsen for those who already lived in the surrounding area previously and research clearly shows a strong distance decay (particularly for poorer communities) in the value of recreational space as its distance from households increases59-61. In other words, local offsetting as currently implemented has the potential to reward the ‘winners’ from developments with ready access to high quality environments, rather than compensating losers for their reduced access to nature34. More importantly though, local offsets ignore the potential for BNG regulation to benefit those who suffer the worst environments, in areas where developers build fewer houses and where local offsetting will rarely apply.

As Figure 1(b) shows, while there is no single, unambiguously dominant, win-win approach to offsetting, by combining natural science and economic insights we can identify alternatives to the status quo which if taken together can provide far superior outcomes than the current practice of local offsetting. Scenario (2) shows that readily available information on the consequences of alternative offsetting sites for species of conservation importance means that a redesigned BNG policy could significantly contribute to policy goals of reversing biodiversity decline. Similarly, Scenarios (4) and (5) show that offsets can significantly enhance access to nature both generally and for disadvantaged communities. Both biodiversity restoration and access enhancements are identified as targets in the UK National Planning Policy Framework25. Therefore, a reformed BNG strategy should consider an efficient mix of dedicated pro-biodiversity, pro-access and pro-equity offsets, each with its targeted and specifically designed policy tools. Our analysis of Scenario (3) provides a warning; a simplistic, accountancy-driven policy of minimising the costs of offsetting produces very poor value outcomes in both biodiversity and access terms. The beguiling attractions of schemes to cut costs must be resisted in favour of principles that boost the net value of outcomes.

Our results provide an illustration of the Tinbergen Rule62,63 that, if there are two (or more) policy objectives which are not perfectly correlated, then a single policy instrument cannot optimise both. Either one accepts this and finds the most preferred trade-off between objectives, or the budget associated with the regulation is divided according to socially optimally outcomes and each objective maximised in line with those allocated resources. Here the objectives of biodiversity gain and access improvement seem most pertinent. Dividing the resources raised by the BNG between Scenarios (2) and (5) would provide a useful alternative to any single strategy.

In a diverse natural and human environment exceptions can occur. While our analysis highlights the inefficiencies of setting up rules which bias outcomes in favour of local offsetting, areas local to a development could of course be chosen of they are indeed the best locations for biodiversity offsetting or the provision of access to nature. Similarly common species should not be ignored especially if they are becoming of conservation concern or contribute to recreational benefits64. However, rules should not be constructed to bias offset decision making into consideration of anything but their intended outcomes. Another consideration concerns ecological fungibility. If offsetting occurs near to the location of ecological loss then problems regarding the comparability or substitutability of species may be less likely to arise. However, such an approach fails to prioritise those species at greatest risk and is therefore less likely to contribute to the wider need to bend the curve on biodiversity loss. Similar arguments can be constructed with regard to recreational access; while local constraints may benefit local communities, they are unlikely to help those disadvantaged groups facing the most degraded environments and at greatest need.

Given the serious flaws evident in current practice, why has this approach been adopted? One likely reason appears to be that flexibility within the biodiversity metric makes it relatively cheap for developers to meet their regulatory liabilities within their own development footprint. Recognised inadequacies in mechanisms for the governance, monitoring or enforcement of on-site biodiversity gains53 also mean that a developer faces lower risks of being found non-compliant with BNG regulations when on-site rather than off-site offsetting is adopted. Secondly, implementing BNG on-site has been perceived by regulators as helping achieve BNG’s explicit policy objective to be ‘of clear benefit to people and local communities’. However, as our results show, such an assertion fails to account for the complexities of such benefits and in particular greatly constrains the potential for offsets to benefit disadvantaged communities. A third, political economy, argument is that local capture of offsetting benefits within planning authorities incentivises these institutions to accept housing development proposals65. A fourth driver of the status quo might be institutional challenges in coordinating the implementation of BNG nationally when the main level of government responsible for the practical implementation of BNG delivery is the local authority. However, evidence on strategic planning gain46 suggests that the intervention of a national level authority, such as Defra, would remove significant and repeated administrative burdens across all planning authorities and hence almost certainly reduce overall costs and improve effectiveness.

The new UK Government has made it abundantly clear that it intends to deliver on its plans to build 1.5million new homes over the next five years but has also informed wildlife NGOs of its intentions to do this in a way that enhances nature66. Our results clearly show that extending the present approach would, at best, be highly inefficient, expensive and fail to seize the real opportunities available to bend the curve of biodiversity loss (and do little to address access inequalities). The core concept underpinning BNG is a sound extension of the polluter pays principle but, as Barber67 notes, in delivering change “Policy is 10% and implementation 90%”; regrettably BNG has provided a further example of an excellent idea, poorly implemented.

A general conclusion, applicable across all regions and countries, is that when policies and their implementation ignore the natural variability in the environment there is always a cost, typically both environmental and social. Within the context of BNG, while the underlying concept is sound and does indeed raise the potential for biodiversity to be incorporated into decision making (a potential which extends well beyond the context of house building), the implementation of this policy incurs major opportunity costs. Tying offsets within the environs of the development that necessitates them ignores the potential for much greater improvements to biodiversity elsewhere. Similarly, from a human perspective, the potential for offsets to address the most needy and disadvantaged communities is negated by constraining them within development planning areas. The simple and very general principle is that ignoring the natural variability of the environment will always impair the effectiveness of the often limited funds available for environmental improvement. We already have the knowledge to make policies and their implementation sensitive to environmental and social variation – we simply need to start using that information.

# **EXPERIMENTAL PROCEDURES**

This section outlines the modelling processes to assess the biodiversity gains, access co-benefits and costs of undertaking offsets in any location across England and to implement the offsetting rules defined by each scenario. Further information is provided in the SI and all output data are available on request.

## **1. Baseline land cover**

The baseline land cover was taken from the CEH 25m resolution raster Land Cover Map (LCM 2000)68. This reports land use across a detailed set of categories a summary of which is provided in SI.

Note that the land use model described below uses agricultural data which, to ensure the anonymity of financial records of individual farmers is aggregated up to a 400ha (i.e. 2 km × 2 km) spatial grid. This data informs the analyst of the precise area (specified to fractions of a hectare) of each land use within the grid square but not the precise location of that area within the grid, thereby ensuring that the private records of each farmer cannot be reconstructed. For this reason, the uncertainty of costing estimates (which are driven by the profitability of land) increases below the resolution of grid square, and we report findings at a consistent 400ha grid level throughout.

## **2. Modelling urban expansion and the demand for offset land**

Expected locations of development and its extent (and hence the area required for offsetting) were determined using the model of urban expansion at constant housing densities over a 25 year period proposed by Eigenbrod, et al. 50 This provided the number of hectares within each grid square converted from farm to developed land over this period. In line with existing environmental policies, areas under forest and peatlands were deemed ineligible for urban expansion. We focussed on housing (rather than industry or nationally strategic infrastructure such as railways, motorways, roads) as the primary contributor to the loss of green spaces in Great Britain69.

## **3. Assessing the biodiversity response to land use change**

The UK Joint Nature Conservation Committee (JNCC) biodiversity modelling framework48, which follows Croft, et al. 70, links biophysical land characteristics, climate related variables and land use to measures of species richness. As such it provides an assessment of the biodiversity consequences of land use change taking into account all the site specific, climate change and other factors which impinge on such response (see SI). The JNCC model was incorporated within the NEV decision support framework47 to assess the impact of land use change on biodiversity at a high degree of spatial resolution across all of England. Assessments were made for 100 at-risk species, representing a variety of taxonomic groups (birds, herptile, invertebrates (including bees, beetles, butterflies, crickets, moths and snails), lichen, mammals and vascular plants), see SI 1.4 for further details.

## **4. Assessing the costs of land use change**

## Given that the costs of converting any of the 9% of England under urban use69 would be prohibitive, and the 10% of land under forest71 is protected (and due to rise very significantly to address net zero commitments)72, then offsets will have to occur on the remaining land, the very large majority of which is agricultural73. The major cost of such land is determined by the opportunity cost of foregone agricultural output. This varies very substantially across England being generally highest in the eastern lowlands where productive soils and an absence of limitations on machinery use across the year result in excellent agricultural returns, and lower in upland areas or where poor soils dominate and waterlogging prevent year-round access for machinery. The simple application of average values would therefore provide highly misleading results in our offset analysis. Use is therefore made of the high spatial sensitivity agricultural model developed by Bateman et al., combining data provided by the UK Farm Business Survey and Agricultural Census55,74,75. This provides grid referenced data stretching from the late 1960s to the present day which, when adjusted to present day prices, provides a rich information source capturing variation in agricultural values across locations taking into account a multitude of biophysical determinants including climate change (see SI). As per the biodiversity analysis, the agricultural model and resultant cost estimator was incorporated within the NEV decision support framework47,54 to ensure consistent assessments.

## **5. Assessing the recreational access co-benefits of land use change and co-benefits minus costs**

## As noted, official guidelines emphasise co-benefits of offsets in terms of recreational access benefits. There is a very substantial literature on the theory and practice of the economic valuation of access to the natural environment76,77. Within this the dominant approach is to assess the preferences and values of individuals as revealed by their recreational behaviour. By examining variation in the number (or absence) of recreational trips from individual’s points of origin (typically their home address) to different sites and taking into account a comprehensive set of determining factors (including the socio-economic and other characteristics of the individual, the availability of other recreational and non-recreational options, the attributes of those options including the type of recreational experience offered, landscape type, environmental quality measures, etc., and the costs of travel and travel time between origin and visited site) the analyst can observe the recreational preferences and values revealed in the choices individuals make.

Data on visitation behaviour is taken from the Monitor of Engagement with the Natural Environment (MENE)78 which uses a nationally representative, household level, annual sample to record the origin and destination of recreational activities. GIS software is used to convert this into travel time and cost estimates which is then combined with census, land use, site and substitute site attribute, linear feature (e.g. rivers) and infrastructure (ranging from major roads to walking path information) data. This data is then analysed within the Outdoor Recreation Valuation (ORVal) model79,80, which uses state of the art revealed preference methods76,77 to assess the number and value of visits to recreational sites by all households across the entire country. The ORVal model allows us to predict how likely it is that an individual will take a trip to a particular greenspace on a particular day. This likelihood differs according to the attributes of the person, the attributes of the greenspace and the attributes of all other available greenspaces. ORVal also allows us to estimate a welfare function which describes how much welfare an individual enjoys as a result of beneficial attributes of a greenspace and how much welfare is lost from each extra pound of cost incurred in travelling to a greenspace. The latter provides an exchange rate that we can use to convert estimates of changes in welfare into equivalent amounts of money as it reveals the amount of welfare that a person considers to be equivalent to having one extra pound. Welfare values for an existing site are estimated by calculating how much each individual’s welfare would fall if they were no longer able to access that site (or how much it would increase with the establishment of a new site) and then converting that welfare quantity into an equivalent monetary amount. The ORVal model and its analytical capabilities is integrated with the offset cost and biodiversity response analyses (detailed above) within the NEV decision support framework47,54.

## **6. Assessing equity weighted access co-benefits of land use change**

Recreational access to the environment is supported on health and equity grounds and features heavily in policy and planning guidelines. A major focus of this debate is on providing such access to those communities suffering the greatest deprivation and the poorest environmental quality. However, while BNG guidelines discuss the importance of recreation, the heavy bias towards local offsetting within policy ignores variation in access environments across the country and the much greater wellbeing that could be generated by locating offsets near to those communities which would benefit most from such opportunities. Instead, local offsetting is skewed to favour the ‘winners’ from developments, those who live in the new houses that have been built (with access preferentially skewed towards those in the most expensive homes) rather than those who have lost the access they used to enjoy prior to this development. More importantly both from a welfare perspective and as a policy priority, the communities who would most benefit from improved access to high quality environments are heavily mitigated against by irrelevant criteria such as the location of recent development. Indeed, the bias towards local offsetting is likely to entrench inequality of access to high quality environments. Such implementation runs directly contrary to government policy to enhance access to high quality recreational green space for those who currently suffer the most degraded environments72. It also ignores HM Treasury guidelines that “When assessing costs and benefits of different options it may be necessary or desirable to “weight” these costs and benefits, depending on which groups in society they fall on.” such that “benefits for lower income households are given a higher social value than the equivalent benefits for higher income households.”81. The weight used in these calculations reflects the marginal utility of income (MUI), the change in utility, or satisfaction, resulting from a change in an individual's income. Drawing on empirical research49 Treasury guidelines recommend a MUI of 1.3 implying that “An additional £1 of consumption received by someone earning £20,000 per year would be worth twice as much than to a person earning £40,000”81, i.e. the benefit of improving environmental access for poorer communities is weighed as being greater than delivering the same change in access for wealthier people.

To apply this weighting procedure across England measures of disposable income after housing costs were retrieved82 for every Middle Layer Super Output Area (MSOA) across the country. This was then compared to median income for the whole country giving an indicator of income deprivation. This was then weighted using the HM Treasury MUI (above) to adjust for the greater value of improvements in access benefits to poorer households. This measure was then applied to the access co-benefits described in the previous section determining the equity weighted recreational access co-benefits of land use change for all locations across England.

## **7. Applying the offsetting rules**

With the biodiversity, cost, co-benefit and equity weighted co-benefits models all integrated within the NEV decision support system, the various offset scenarios were implemented through two forms of algorithm. For scenario (1) Local offsetting (the status quo), a simple distance-based algorithm was applied which searched for the closest location to the development site providing an equivalent area of farmland for offsetting. For all other scenarios, (2) to (5) inclusive, a standard ordering algorithm was used to locate the offset area. So, for Scenario (2) Maximise conservation priority, the JNCC species models within NEV were run for all areas of England, hypothesising that each area in turn was converted from farmland to semi-natural grassland and the biodiversity implications assessed. Each area was then ranked from the highest (best) to lowest (worst) biodiversity response. The required offset area was then allocated starting with that location which gave the highest gain in biodiversity and proceeding down this ranking until the required total area of offset was reached. This highest to lowest ranking approach was also used for Scenarios (4) Maximise co-benefits minus costs and Scenario (5) Maximise equity weighted co-benefits. For Scenario (3) Minimise costs, the ranking was ordered from lowest to highest cost areas with the former being selected first and this list being worked down until again the required area for offsetting had been delivered.

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## **8. Limitations of the modelling approach**

Integrated modelling approaches at large scale rely on a series of assumptions that limit their capability of predicting the future, in particular given that they are often, as in this work, deterministic in nature, are numerically complex limiting the possibility of exploring future ranges of outcomes and, if estimated statistically on the basis of observed empirical data, might not be able to fully capture changes that are out of the estimation sample. While this is true of most models, we do recognise that models are useful to understand processes and dynamics and, as in this case, the relative performance of different policy-driven land use changes with the objective of offsetting nature as a result of urban development; this is because we are interested in the relative performance of different policies under same baselines, rather in absolute numerical outcomes. However, a number of limitations associated with the modelling approach chosen must be acknowledged, namely, 1) the deterministic nature of the models, which do not provide a measure of the uncertainty associated with the outcomes obtained; 2) the lack of feedback loops which can alter the sets of conditions determining the predicted land use changes. For example, we assumed that future projections of urban land uses follow historic trends driven by projections of population increases. In addition, the costs of offsetting land are represented by the foregone agricultural income of the areas where offsets are created. However, changes in land values from previous urbanisation (and offsetting) are not accounted for in our modelling setting. Equally, other policies also affecting land use (such as planting trees to achieve Net Zero or promoting land-based renewable energy production) which have the potential to significantly alter land use trajectories and associated values are not included in the analysis. These issues affect all of our analyses including those of current practice. Nevertheless, it is worth noting that all the models collated into the integrated modelling suite of this work are temporally dynamic in the sense that they respond and predict future land uses and associated provision of ecosystem services on the basis of an adaptive behaviour of farmers driven by climate change. As such, the agricultural opportunity cost is an annuity of the flow of gross margins accounting for changes of farming behaviour into the future driven by climate change; equally, species responses to land use change are also driven by climate.Finally, it is important to acknowledge that as of themselves the fact that the alternative scenarios (e.g. ‘maximize biodiversity’ and ‘minimize costs’) provide the best outcomes for biodiversity and costs (etc) respectively is not surprising. These scenarios are deliberately designed to achieve these outcomes so as to achieve the main goal of the case study: to act as counterfactual scenarios against which the current implementation of BNG can be compared.

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The idea for the analysis was conceived by IJB, BHD and MM and developed in collaboration with EJM-G and MF. Analyses were undertaken by MM and RC with support from IJB, AB and FE. Models were developed by AB, BHD, FE, CF, NO, MM and EW. The paper was written in collaboration with all authors.

**DECLARATION OF INTERESTS:**

The authors declare no competing interests.

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**FIGURE TITLES AND LEGENDS**

**Figure 1:** Alternative scenarios for Biodiversity Net Gain (BNG) offset rules. **(a).** The location and area of offsets under each scenario: (1) Local offset (status quo); (2) Maximise conservation priority; (3) Minimise costs (market allocation of offset locations); (4) Maximise co-benefits (access for recreation) minus costs; (5) Maximise equity-weighted co-benefits. **(b).** Radar chart comparing the relative performance of the BNG scenarios across four criteria: Maximum biodiversity; Minimum costs; Maximum co-benefits minus costs; Maximum equity weighted co-benefits **(c).** Scenario specific values for four measures: (i) Gains in species richness for species of conservation priority; (ii) Costs; (iii) Co-benefits; (iv) Co-benefits minus costs.

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