Title: Developing a Nature Recovery Network using systematic conservation planning

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Developing a Nature Recovery Network using systematic conservation planning

Abstract

Conservation area networks in most countries are fragmented and inadequate. To tackle this in England, government policies are encouraging stakeholders to create local-level Nature Recovery Networks. Here we describe work led by a wildlife organisation that used the systematic conservation planning approach to identify a Nature Recovery Network for three English counties and select focal areas within it where they will focus their work. The network was based on identifying core zones to maintain current biodiversity and recovery zones for habitat restoration, meeting area-based targets for 50 priority habitat, landscape, landcover and ecosystem service types. It included the existing designated sites for conservation, which cover 6.05% of the study site, and identified an additional 11.6% of land as core zones and 18% as recovery zones, reflecting the organisation's broad objective of conserving and connecting 30% of England by 2030. We found that systematic conservation planning worked well in this context, identifying a connected, adequate, representative and efficient network and producing transparent and repeatable results. The analysis also highlighted the pressing need for government agencies to provide national-level guidance and datasets for setting targets and including species data in spatial planning, creating a national framework to inform local action.

Introduction

Site-based conservation is one of the most widely used approaches for maintaining and restoring biodiversity and other forms of natural capital. However, existing protected areas and OECMs (other effective area-based conservation measures) are failing to achieve their conservation goals (Maxwell et al. 2020), partly because many conservation area networks are small, fragmented and limited to land and sea with low economic value, often missing important biodiversity (Pressey & Tully 1994; Shwartz et al. 2017; Cunningham et al. 2021). This has led to calls from around the world to expand current conservation area systems, creating ecological networks that will conserve biodiversity in the long-term (Dinerstein et al. 2019). This is exemplified by England, one of the four devolved nations of the United Kingdom (UK), which has seen a step-change in conservation thinking. Building on a mantra of 'more, bigger, better and joined' (Lawton et al. 2010), there is now a focus as part of the UK Government's 25 Year Plan to develop Nature Recovery Networks that will conserve biodiversity, improve landscape resilience to climate change, strengthen ecosystem services and improve wellbeing through increased access to nature (Defra 2018). This has been bolstered by recent government commitments to protect 30% of the UK's land by 2030 (Defra 2020a) and to embed Nature Recovery Networks in Local Nature Recovery Strategies, which will be stakeholder-driven local plans to guide conservation and restoration actions (Defra 2018).

The most widely used approach for designing conservation area systems and other ecological networks is systematic conservation planning (Margules & Pressey 2000; Sinclair et al. 2018). This identifies sets of priority areas for conservation management based on the concepts of connectivity, adequacy, representativeness and efficiency. These concepts match up well with the principles behind Nature Recovery Networks (Crick et al. 2020), so there is growing interest in whether systematic conservation planning could help guide these new initiatives. This is important because ecological networks in the UK have traditionally been designed either solely based on expert opinion, which can lack transparency and repeatability (Drescher et al. 2013), or by weighting and summing different types of spatial data, which often fails to represent biodiversity adequately (Pressey & Nicholls 1989). Here we present results from the first analysis to use systematic conservation planning to develop a fine-scale Nature Recovery Network for three counties in England, providing evidence for conservation policy-makers and planners on the suitability of this approach.

There are three important issues that must be taken into account when designing terrestrial ecological networks in England. First, much of the country is agricultural land, with most biodiversity restricted to small fragments of semi-natural habitats (Lawton et al. 2010). Second, almost all of the land is privately owned (Jackson & Gaston 2008) and so networks often have to be pieced together, working with landowners who are willing to manage their land for conservation (Franks 2019). Third, conservation and restoration activities are undertaken by a number of individuals and organisations and funded through a similarly diverse set of schemes (Shwartz et al. 2017). All of these make systematic conservation planning particularly suitable because it is designed to develop a shared vision and set of objectives at a landscape level, whilst also accounting for site-level context (Groves & Game 2015). However, most of the literature on developing ecological networks implicitly assumes that work is overseen and coordinated by one group. This is rarely the case in countries where conservation involves a range of actors (Redford et al. 2003), so this study shows how systematic conservation planning can be used to inform actions at a range of different scales and institutional levels.

The ecological network was developed by Berkshire, Buckinghamshire and Oxfordshire Wildlife Trust (BBOWT), an NGO that forms part of the UK-wide Wildlife Trusts. Their reasons for undertaking this project were threefold. First was to identify a potential Nature Recovery Network for the three counties (Figure 1), producing maps that can be used to guide the organisation's action on the ground. Second was to identify priority areas within the Nature Recovery Network where BBOWT should focus their work, based on the presence of features that are particularly important to the organisation. Third, it provided an opportunity to test the relevance of the approach for terrestrial planning in the UK and, if successful, to provide an example when advocating its adoption by other Wildlife Trusts and more broadly (Crick et al. 2020). To address these three goals, we used the Marxan (Ball et al. 2009) and MinPatch (Smith et al. 2010) spatial prioritisation software packages to identify a potential Nature Recovery Network within this highly transformed and fragmented landscape. Through expert consultation, we produced a list of important conservation features and specified targets for how much of each should be included in the ecological network, identified a set of priority areas for their conservation and restoration and then mapped areas within this broader network where BBOWT should focus their resources.

Methods

Setting the objectives and conservation features

The prioritisation process was designed to inform BBOWT's three broad objectives outlined above. BBOWT decided that the objectives would be best met by identifying a Nature Recovery Network consisting of "core" and "recovery" zones, with the remaining land outside the network classified as belonging to a "wider landscape" zone. The core zones would be managed to maintain their current biodiversity; the recovery zones would be managed to improve the ecological condition of existing habitat and increase habitat coverage through restoration. They also decided that the overall extent of the network should be 30% of the planning region, based on The Wildlife Trusts call to conserve and connect 30% of the country by 2030 (The Wildlife Trusts 2021).

Once these objectives were established, we brought together a team of BBOWT ecologists and conservation managers to produce the list of elements for representing biodiversity and other forms of natural capital in the network (referred to as 'conservation features' hereafter) and decide whether they should be represented in the core or recovery zone. The selection of conservation features was also based on data availability and we only considered datasets that covered all three counties, in some cases ignoring higher quality data that was only available for one county. This expert group decided that the core zone should conserve 15 habitat types (Table S1), whereas the restoration zone should contain 3 habitat types, 4 BBOWT living landscapes, 7 landcover types, 8 habitat types with potential to be restored to priority habitat and 13 greenspace features around urban areas (Table S1). We originally planned to include species data in the prioritisation process, mostly as indicators of habitat quality or functional connectivity. However, we could not use the raw available species distribution data because it showed strong sampling bias, with most records coming from urban centres and popular nature reserves. We tried to overcome this bias by using the data to produce fine-scale species distribution models based on landcover and climate layers, but while the resultant maps were effective at predicting the status of the presence/absence points used in the analysis, the expert group were concerned that the results did not reflect the actual distributions of the species, probably because the available environmental variables were unsuitable (Fourcade et al. 2018). This meant we did not use species as conservation features in our analysis.

Mapping the different conservation features was relatively straightforward. For the core zone features we used the Natural England Priority Habitat Inventory polygon dataset (Natural England 2019) to map the coastal and floodplain grazing marsh, deciduous woodland, good quality semi improved grassland, lowland calcareous grassland, lowland dry acid grassland, lowland fens, lowland heathland, lowland meadows, open mosaic habitat, purple moor grass and rush pastures and reedbeds. We used other datasets provided by Natural England for traditional orchards (Natural England Open Data 2020a) and wood pasture and parkland (Natural England Open Data 2020b). We also used the Natural England polygon dataset on ancient woodland to map the ancient and semi-natural woodland habitat type (Natural England Open Data 2021). For the recovery zone, we also used the ancient woodland dataset to map the ancient and replanted woodland habitat type. We mapped ponds using the OSM dataset (OpenStreetMap 2020), avoiding the inclusion of man-made features such as reservoirs by removing polygons that were larger than 2 ha based on the Freshwater Habitats Trust definition of a pond (Williams 2010), and mapped rivers as lines using the Ordnance Survey Open Rivers dataset (Ordnance Survey 2020).

We used the CEH landcover 25 m resolution raster dataset (CEH 2016) to identify and map the important landcover types, which we defined as those containing natural or semi-natural habitats (Table S1). Land with potential to be restored to priority habitat was based on the Natural England national habitat network maps, which identifies patches of land with high restoration potential based on proximity to primary habitat, land use (urban/rural), soil type and slope (Edwards et al. 2020). In some cases, a patch of land has the potential to be restored to several different habitat types, so the BBOWT team prioritised between the habitat types and then assigned each patch to the most important habitat type. Their decision was based on favouring habitat types that have a limited extent in the three counties and nationally and they prioritised (with most important first): lowland heathland, lowland meadows, lowland dry acid grassland, lowland calcareous grassland, lowland fens, purple moor grass and rush pastures, reedbeds, and deciduous woodland. We then produced these 8 habitat network maps based on the Network Enhancement Zone 1, Network Enhancement Zone 2 and Habitat Restoration-Creation categories (Edwards et al. 2020). For the BBOWT Living Landscapes we used polygon data mapping their boundaries (BBOWT 2013). For the features based on urban greenspace availability, we identified significant urban centres that are to be the focus of BBOWT public engagement activities (e.g., community programmes, and education) based on selecting towns and cities with a population of greater than 100,000 people. We then produced circular polygons with a radius of 10 km around the centroid of these urban areas. Finally, we used QGIS (QGIS.org 2019) to identify natural habitat and farmland from the CEH landcover dataset falling within these buffers. We used this to produce separate maps showing greenspace around each of the 13 urban areas (Table S1).

Targets for each conservation feature in the core and recovery zones were set by the expert group through an iterative process designed to ensure the Nature Recovery Network met the broad objectives set out by BBOWT (Rondinini & Chiozza 2010). The final system classified each terrestrial habitat conservation feature as being of Low, Medium or High importance, based on their biodiversity value and their total area within the planning region and nationally, and then set targets of 20%, 50% and 80% respectively of their current distribution (Table S1). The other targets ranged between 20% for eleven features and 100% for rivers (Table S1). Where targets were set as less than 100% for the habitat and landcover types, it was emphasised by the expert group that the remaining extent still has conservation value and should be managed appropriately in the wider landscape.

Producing the planning system

Our planning region consisted of Berkshire, Buckinghamshire and Oxfordshire. We divided this up into a series of planning units, which were based on a layer of 10 ha hexagons that were produced using the Create Grid function in QGIS. We then used the Union function in QGIS to combine these boundaries with polygons showing the boundaries of the current National Nature Reserves, Sites of Special Scientific Interest, Local Wildlife Sites and BBOWT reserves. This meant the final planning unit layer divided the three counties into a series of hexagons and sub-sections of hexagons to match the designated site boundaries. We then used the CLUZ extension in QGIS (Smith 2019) to create the three counties conservation planning system based on these planning units.

Figure 1

In CLUZ we specified that the planning units that represented sections of the existing designated sites should have "Conserved" status, so that they would always be selected in the prioritisation process. We also used CLUZ to exclude planning units with high levels of urbanisation, as the BBOWT team decided that these should not be selected as priority areas for conservation management. We identified planning units to be excluded by using the built-up areas boundary dataset (ONS 2017), converting it to a 25 m resolution raster layer using ArcGIS and using the Tabulate Area function to calculate the area of built-up land in each planning unit. Planning units that did not contain any of the conservation features and were also 50% or more built-up land were set as "Excluded". We then imported the vector and raster conservation feature data into CLUZ, which calculated the amount of each feature in each planning unit. We also specified the targets in the target table, so that CLUZ automatically calculated how much of each target was already met by the designated sites.

The planning unit cost was based on the 'Provisional Agricultural Land Classification' layer (Natural England Open Data 2018) because that is the main land use in the planning region. This layer classifies agricultural land into five grades in England, with the best land being Grade 1, based on criteria that account for climate (temperature, rainfall, aspect, exposure, frost risk), site (gradient, micro-relief, flood risk) and soil (depth, structure, texture, chemicals, stoniness). We inversed the scale used in the original dataset to produce an opportunity cost metric, so that the highest quality land had a cost of 5 and the lowest quality land had a cost of 1. We then converted this vector layer into a 25 m resolution raster dataset using QGIS and reclassified it so that urban and woodland areas, which were ungraded in the original layer, were given a value of 1 to match that of the lowest quality agricultural land. We then used the Zonal Statistics QGIS plugin to sum the values of all the pixels found in each planning unit and added these data into the planning unit cost field in CLUZ.

The spatial prioritisation process is based on selecting planning units that are needed to meet the different conservation feature targets. In the three counties, as in most of the UK, important habitat types are highly fragmented and so planning units that are selected to meet targets often also contain large amounts of agricultural and urban land. In such cases, reporting the area of the selected planning units can exaggerate the area of land required for conservation management. To overcome this, we used QGIS to measure for each planning unit the combined area of land covered by core zone conservation features and the additional combined land covered by recovery zone conservation features. We then calculated the area of land containing these features in the nature recovery network we identified.

Running the analyses

We used a four step process to develop the Nature Recovery Network using the Marxan spatial prioritisation software (Ball et al. 2009) and MinPatch function in CLUZ (Smith et al. 2010). While our analysis identified three management zones (Core, Recovery and Wider Landscape) we did not use Marxan with Zones (Watts et al. 2009) because our initial analyses found the results produced outputs where the zone types consisted of too many small patches. Marxan uses an approach based on simulated annealing to identify portfolios of planning units that minimise the portfolio cost, which is the sum of the combined planning unit costs, any penalty costs for not meeting targets and a boundary costs based on the external edge of the selected planning units. The user can then influence whether the results consist of scattered planning units or bigger patches by changing the Boundary Length Modifier (BLM) value, where a higher value produces less fragmented results. An analysis involves running Marxan a number of times, with each run identifying a near-optimal portfolio, so that the “best” portfolio is then identified as the one with the lowest cost (Ball et al. 2009). Marxan also produces a selection frequency output based on counting the number of times each planning unit appears in each of the runs.

We first used Marxan to identify the planning units needed to produce the Nature Recovery Network as a whole, meeting both the core zone and recovery zone targets. We created the Marxan input files using CLUZ and then carried out an analysis based on 100 runs of 100 million iterations, saving the portfolio output from each run. We used a BLM value of 0.25 based on trial and error to produce results that were not overly fragmented but did not select large areas that were not needed to meet the targets. Second, we used MinPatch to modify each of the 100 portfolios identified by Marxan. MinPatch works by: (a) removing patches from the Marxan output that are smaller than the specified threshold; (b) adding new circular patches of a specified size to meet all the targets, and; (c) removing any superfluous planning units that are not needed to meet the targets or minimum patch size constraint (Smith et al. 2010). For our analysis we specified that each patch of planning units should be at least 50 ha, other than any small designated sites that were automatically included in the outputs, and that the new circular patches should have a radius of 450 m, so that the resultant priority areas would be roughly circular (Smith et al. 2010). MinPatch also calculates the best output as the one with the lowest portfolio cost, and this best portfolio was used as the Nature Recovery Network.

For the third step we used CLUZ to exclude all the planning units that were not selected to be part of the Nature Recovery Network. We then reran Marxan but this time we set the targets for the recovery zone features as 0, so that Marxan would only identify where the core areas should be located within the broader network. Some of the planning units in the core zone contained features associated with the recovery zone, so these sites would have to be managed for conservation and restoration to ensure they helped meet the targets for all the features found within them. The analysis was once again based on 100 runs of 100 million iterations with a BLM of 0.25. Fourth, we identified where BBOWT should focus their resources by first identifying patches of planning units within the network that contain the habitat types identified as a High or Medium priority for the organisation (Table S1). We then calculated the area of each of those planning unit patches and selected those with an area > 10,000 acres or 4,047 ha.

Results

The planning region has a total area of 574,838 ha and 6.05% of this is in the 1,988 sites that are already designated for conservation. These protected areas meet all the greenspace accessibility targets, as well as targets for 14 landcover and priority habitat types (Table S1). Of the 23 conservation features where the targets are not met by the designated sites, 16 features have less than half of their targets met (Table S1).

The Marxan analysis to meet all the targets identified planning units throughout the planning region, especially in two bands running south-west to north-east through the Upper Thames Clay Vales and Midvale Ridge ecoregions and the Chilterns Hills (Figure 2**Error! Reference source not found.**a; Figure S1). The majority of the selected areas had high selection frequency scores, most notably the river systems found throughout the planning region, but scores were generally lower in the Chilterns, meaning that these planning units could be replaced in the portfolio with other, similar sites (Figure 2**Error! Reference source not found.**b; Figure S1). The MinPatch analysis removed a number of small patches from the Marxan portfolios (Figure 2c) but this had a negligible impact on the selection frequency scores (Figure 2d). The Marxan analysis to identify the core zone identified a number of patches of different sizes within the network (Figure 2e), almost all of which had high selection frequency scores and so could not be replaced by other planning units while still meeting the targets (Figure 2f).

The proposed Nature Recovery Network meets all the targets (Table S1) and consists of planning units with a combined area of 189,979 ha (Figure 3), although the area of land needing conservation management within these planning units would by 169,925 ha (29.6% of the planning region). The planning units in the core and recovery zone have a combined area of 67,649 ha and 122,330 ha respectively (Figure 3), although the area of land requiring conservation management within these planning units would be 66,700 ha and 103,225 ha (11.6% and 18% of the planning region respectively). We also identified seven BBOWT focal areas i.e., patches of planning units within the landscape that met the 10,000 acre (4,047 ha) size threshold, and their areas ranged from 4,351 ha to 39,735 ha (Figure 3). The area of land needing conservation management within these planning units is 81,554 ha, which is 48.0% of the land needing conservation management in the network and 14.2% of the planning region.

Figure 2

Figure 3

Discussion

The UK has a long history of identifying networks of priority conservation areas at a sub-national scale. These have generally been designed by small groups of experts or by weighting and combining spatial data to identify networks that are rich in particular features. Such processes capture important local knowledge on biodiversity and conservation opportunities (Cowling et al. 2003) but they often lack transparency, rarely account for opportunity costs and generally identify networks that fail to represent biodiversity adequately (Williams et al. 1996; Game et al. 2013; Cunningham et al. 2021). Systematic conservation planning was designed to address these issues, so in this section we discuss how we used the approach to identify an effective Nature Recovery Network (Rodrigues & Cazalis 2020).

Translating the context into targets

The first steps of systematic conservation planning involve translating the background context into broad objectives and then specific targets (Groves & Game 2015). The main objectives underpinning this project comes from UK government policy (Defra 2018), which has identified Nature Recovery Networks as an important policy instrument that should be developed at a sub-regional level by a large range of stakeholders (Crick et al. 2020). Different groups in England are using different methods to help design these networks and this provides the second part of this project's context, as BBOWT were keen to trial a systematic conservation planning approach, both to illustrate how it could be used for terrestrial planning in the UK and to guide their work within Berkshire, Buckinghamshire and Oxford. More specifically, the objectives and targets were based on The Wildlife Trusts goal to start putting nature into recovery across at least 30% of land and sea by 2030 (The Wildlife Trusts 2021).

This context led to BBOWT's decision to use the analysis to identify three types of zone. The "core" and "recovery" zones were defined to fit with government recommendations on designing Nature Recovery Networks. However, in other contexts it might be more appropriate to build networks with more zones, for example by distinguishing between habitat improvement and creation (Isaac et al. 2018). The "wider landscape" zone was defined to make it clear that areas outside the network also contain valued biodiversity and ecosystem services. This became particularly important when initial analyses showed that setting 100% targets for each of the priority habitats selected around 40% of the planning region, far exceeding the 30% broad objective and leading us to reduce these targets. Thus, our proposed Nature Recovery Network does not include every patch of each priority habitat (Table S1), even though the National Planning Policy Framework states that local plans should promote their conservation (Department of Communities and Local Government 2019). Instead, targeted conservation action will be needed to conserve these patches within the wider landscape, together with policies and actions to maintain and enhance broader biodiversity (Crick et al. 2020). This will help achieve BBOWT's aim that the wider landscape becomes more ecologically permeable and less hostile to wildlife, benefitting common species, as well as those that are threatened or rare.

Most of the systematic conservation planning analyses described in the literature that identify a specified percentage of a landscape use a "maximum coverage" approach (Wilson et al. 2009), which involves identifying the best planning units by defining a benefit function and weighting for each conservation feature (Moilanen et al. 2009). We adopted a "minimum set" approach, using Marxan to identify the best portfolio of planning units for meeting targets for each conservation feature (Ball et al. 2009). This involved a series of iterations to adjust the targets until the proportion of the planning region selected by Marxan was similar to our 30% objective (Rondinini & Chiozza 2010), reflecting the broader context and value systems that underpin them (Smith et al. 2019). We adopted this approach because specifying targets for each conservation feature made the process easier to understand and more transparent for the BBOWT group (Carwardine et al. 2009). In particular, it helped identify conservation features that are poorly represented in the current network of designated sites, to visualise how much extra land would be needed to meet different targets and to discuss the relative importance of conserving or restoring the different features. Setting targets also helped achieve consensus (Game et al. 2011), identifying where often contentious issues were not a problem within the planning region. For example, there were initial concerns that including features based on access to nature would skew the selection to areas near towns, which would have negative impacts on those habitats that are vulnerable to human disturbance. However, these concerns were allayed once it became clear that greenspace targets could be met without selecting areas containing these sensitive priority habitat types.

Designing the network

We originally planned to use Marxan with Zones to design the Nature Recovery Network, as this could assign each planning unit to one of the three zones used in our analysis (Watts et al. 2009). However, due to the fragmented nature of the different conservation features, we found from pilot analyses that the software identified a very large number of small interspersed patches of each zone type, which would have been difficult to demarcate and manage. Instead, we used Marxan and MinPatch to identify the network, and then Marxan to identify the core zones within the network. Using MinPatch we removed patches of planning units that were deemed too small to form part of the network (Smith et al. 2010), although in our analysis this made little difference to the results. This occurred because the river system is inherently connected and the network habitat layers are designed to identify where to link up patches of priority habitat (Edwards et al. 2020), so meeting their targets ensured that Marxan selected large, joined up patches of planning units. This was important because, while Marxan allows the user to influence the patch size of the planning unit portfolios it identifies, it does not automatically select areas that link these different patches. This can be addressed by using new versions of Marxan that incorporate data on connectivity (Daigle et al. 2020), or by carrying out *post-hoc* analyses that identify which of the portfolios identified by Marxan analyses score best for different connectivity metrics (Fajardo et al. 2014). However, in the absence of data to guide these processes, our work shows that similar results can be achieved by setting high targets for features that already provide connectivity.

One issue that we encountered in our study that is not well addressed in the literature is how to account for high levels of habitat fragmentation. Our planning unit layer was based on a series of 10 ha hexagons, which is much smaller than most spatial prioritisations described in the literature (Álvarez-Romero et al. 2018; Botts et al. 2019), but to meet all the targets Marxan still had to select some planning units that mostly contained agricultural land of little conservation value. One solution would have been to use smaller planning units but Marxan would have produced less efficient solutions with a larger number of smaller hexagons (Ball et al. 2009). Instead, we calculated and reported the area of land in each planning unit covered by the conservation features, finding that while the selected planning units covered 35.2% of the planning region, the land within them needed for conservation or restoration covered 30.9%. This suggests that future work would benefit from accounting for this fragmentation, either by using smaller planning units together with integer linear programming software to produce more efficient results (Schuster et al. 2020), or by creating planning units based on patches of similar land-use types so that priority habitats can be selected without also selecting less important agricultural land (Sykes 2020).

Our analysis also outlined an approach for organisations to define how their work can fit within broader conservation goals. Many organisations do this implicitly, but making this process transparent is particularly important when developing ecological networks in countries like the UK, where landscapes consist of many land parcels owned by a range of individuals and organisations (Crick et al. 2020). BBOWT developed a simple approach that identified a subset of conservation features, based on their importance for the organisation and its membership, and the extent to which they are likely to be conserved by other conservation groups. We then identified large patches of these priority habitats, where BBOWT could be confident that conservation management would achieve their broad objectives. As with the broader analysis, part of the reason for this final stage was to illustrate the benefits of transparently defining priorities at an organisation level. One eventual goal would be to encourage all the organisations working in the planning region to come together and define their objectives, helping identify synergies and gaps, avoid unnecessary overlap and ensuring that funding scheme criteria can be best matched to local priorities (Smith et al. 2009). Such a collaborative and multi-stakeholder approach will also be needed to develop the county-level Local Nature Recovery Strategies that are a fundamental component of the proposed Environment Act (Defra 2020b).

Future work

Until recently, systematic conservation planning had only been used in the UK to help design ecological networks in the marine realm (Lieberknecht & Jones 2016). This is beginning to change, partly because the approach is ideally suited to situations where a large number of stakeholders are seeking to achieve a range of objectives (Groves & Game 2015). Our work illustrates the benefits, showing how international, national and local objectives can be translated into a fine-scale maps based on a shared vision and set of targets.

The BBOWT Nature Recovery Network presented here is designed as a decision-support tool for their staff, helping inform and guide their conservation and community engagement work over the next 5-year strategic planning period (BBOWT 2021). This will involve: acquiring new nature reserves; developing conservation projects and partnerships with landowners, councils, and other NGOs to implement new management for wildlife; providing support and advice for other landowners, and; empowering community groups to act to support nature’s recovery. However, the organisation is relatively small and their work will not have a direct impact on the entire network.

Instead, the results presented here will be used by BBOWT to concentrate their limited resources on new projects in the focal areas within the network (Figure 3). This will provide opportunities to explore new approaches to conservation, such as rewilding to help create wilder and more connected landscapes, and habitat creation and restoration to achieve Biodiversity Net Gain and deliver nature-based solutions for flood management, carbon sequestration and other important ecosystem services. The Nature Recovery Network will also provide access to good quality natural greenspace for priority cities and towns (Natural England 2010), and these areas will be the focus of BBOWT's engagement activities such as community programmes and education.

Developing the Nature Recovery Network was aided by the availability of spatial data on priority habitats, which have been defined, identified and mapped by Natural England (Natural England 2019). These open-source datasets have limitations, so there are ongoing efforts at the national and local level to produce more up-to-date and accurate data, but these maps are widely known and used by practitioners, so it was easy to incorporate these national priorities into our local plans. Unfortunately, there is no equivalent for priority species, and while many of England's rarest and threatened species have been listed in legislation (NERC 2006), there is little guidance on how this list should be used to inform priorities for spatial planning. Just as importantly, we lack fine-scale, spatially consistent and easily available distribution data for most of these species. This is one reason why we did not use any species as conservation features in our analyses, and while the analysis accounted for a representative set of habitats and landcover types, it would have benefited from including species as conservation features both as proxies for habitat quality and to ensure they were adequately represented (Noss 1987). This means there is a pressing role for Natural England to provide national-level guidance and data for species, supporting the existing networks of local environmental record centres and creating a national framework to inform local action.

Developing guidance for local conservation target-setting should also be a priority, as at present targets have only been set at the national level. These provide helpful context but more is needed to translate them into sub-national targets that reflect conservation value. For example, the 30% national protection target should probably involve some counties conserving less of their land and others conserving more (Dallimer & Strange 2015; Garibaldi et al. in press). Just as importantly, specific advice is needed to set targets for the UK's different priority habitats and species to help ensure their long-term persistence. Such targets would play a critical role in developing Nature Recovery Networks but they could also play a major part in guiding new and proposed conservation land acquisition programmes (Oetting et al. 2006), local nature recovery strategies, afforestation and agri-environment schemes (Shwartz et al. 2017; Villarreal-Rosas et al. 2020), and environmental net gain (Simmonds et al. 2020). In doing so, the systematic conservation planning approach could underpin a range of national policies and local practices (Botts et al. 2019), providing the types of decision support tool we need to make informed and effective choices.

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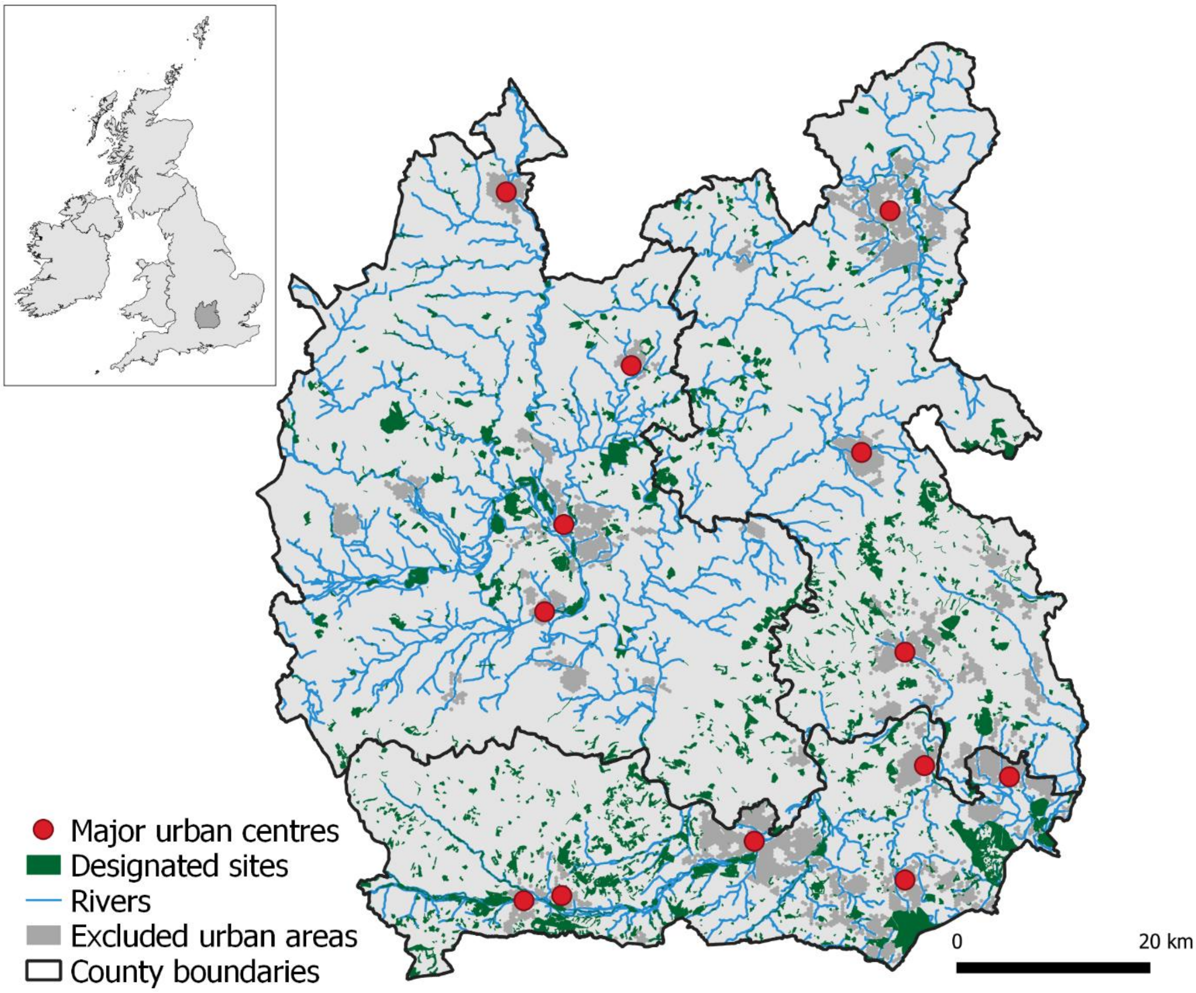

Figure 1: The planning region consisting of the counties of Berkshire in the south, Buckinghamshire in the east and Oxfordshire in the west, showing urban centres used in the analysis (population > 100,000), designated sites for nature, rivers and urban areas that were excluded from selection in the spatial conservation prioritisations.

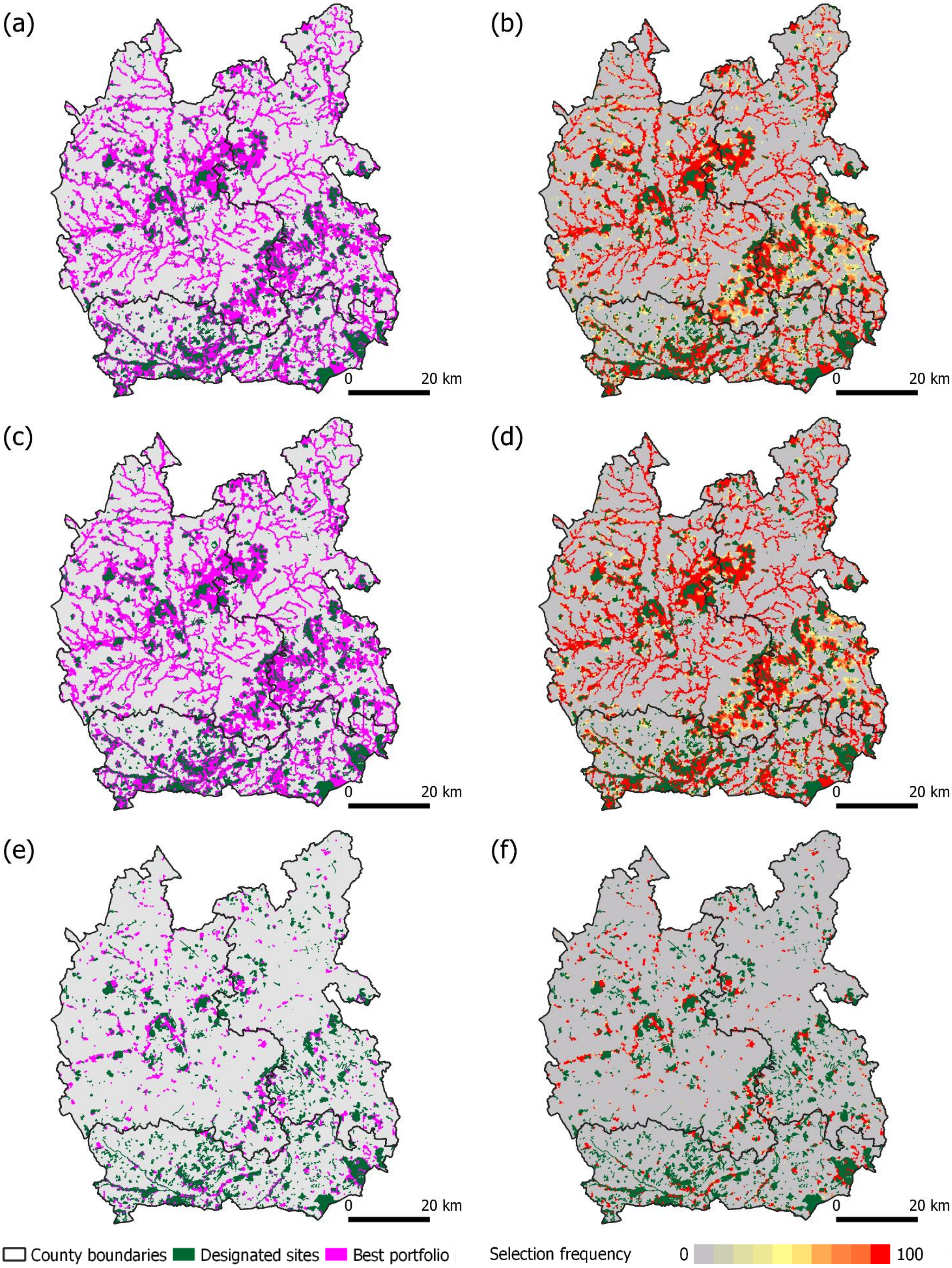

Figure 2: The analysis outputs for the three main stages used to develop the Nature Recovery Network showing: the Marxan best portfolio (a) and selection frequency output (b) for meeting all the targets; the MinPatch best portfolio (c) and selection frequency output for meeting all the targets (d), and; the Marxan best portfolio (e) and selection frequency output (f) for meeting the core zone targets within the Nature Recovery Network.

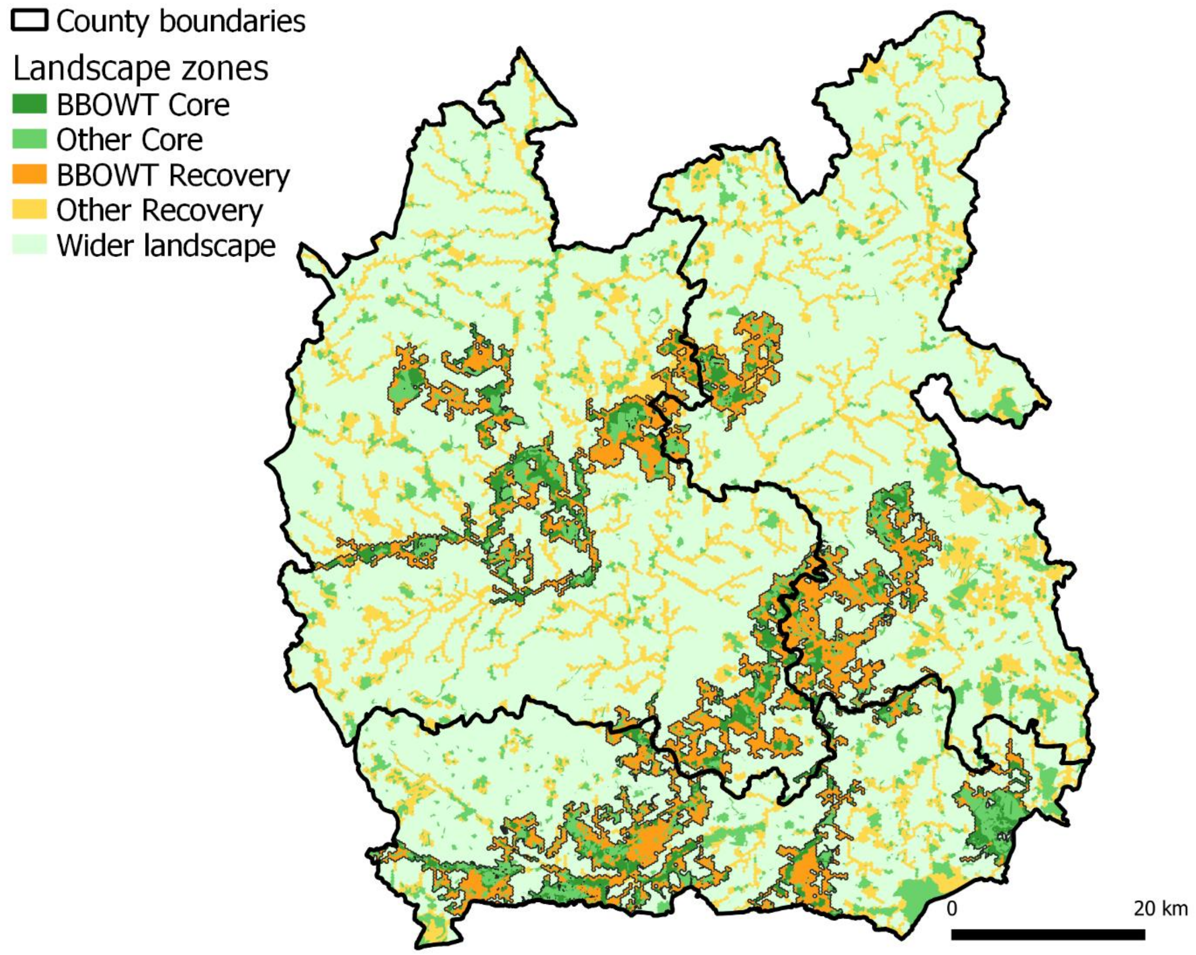

Figure 3: The proposed Berkshire, Buckinghamshire and Oxfordshire Nature Recovery Network consisting of the core zone (which includes the designated sites for nature), recovery zone for habitat creation and restoration and the wider landscape zone. Darker colours indicate sections of the network that were identified as BBOWT focal areas based on the presence of large patches (>10,000 acres or 4,047 ha) of BBOWT priority conservation features.

Supplementary material

Table S1: Details of the conservation features used in the spatial conservation prioritisation, showing their targets for the Zone 1 (core) and Zone 2 (recovery) and their area in the existing designated sites, proposed Nature Recovery Network (NRN) and the planning region of Berkshire, Buckinghamshire and Oxfordshire. All values are measured in hectares apart from rivers, which are measured in km.

Feature type	Name	BBOWT priority	Target (ha or km)	Amount in designated sites (ha or km)	Amount in NRN (ha or km)	Amount in planning region (ha or km)	Details
Habitat type	Lowland calcareous grassland	High	1,801	1,517	1,996	2,252	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Lowland dry acid grassland	High	277	202	293	346	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Lowland fens	High	203	237	252	254	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Lowland heathland	High	548	621	679	685	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Lowland meadows	High	1,664	1,410	1,800	2,080	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	No main habitat, additional habitats present	Low	1,167	2,194	3,847	5,835	20% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Purple moor grass and rush pastures	Low	10	31	51	52	20% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Reedbeds	Low	6	30	32	32	20% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Ancient and Semi Natural Woodland	Medium	8,198	9,555	12,527	16,395	50% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Good quality semi-improved grassland	High	2,638	420	2,639	3,298	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Traditional orchard	Low	151	21	231	755	20% of total in Zone 1 (Nat Eng et al, 2020a)
Habitat type	Deciduous woodland	Medium	21,830	16,967	28,483	43,659	50% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Coastal and floodplain grazing marsh	High	5,376	1,154	5,908	6,719	80% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Open mosaic habitat	Low	375	522	955	1,875	20% of total in Zone 1 (Nat Eng et al, 2019)
Habitat type	Wood pasture and parkland	Medium	13,260	5,774	13,486	26,520	50% of total in Zone 1 (Nat Eng et al, 2020b)

Habitat type	Ancient replanted woodland	Low	1,631	4,097	5,499	8,154	20% of total in Zone 2 (Nat Eng et al, 2019)
Habitat type	Rivers	No	92	9	93	97	100% of total in Zone 2 (Ordnance Survey)
Habitat type	Ponds	No	1	0	1	4	20% of total in Zone 2 (OSM)
Living landscape	Bernwood Forest and Ray Valley	No	15,039	2,815	15,040	21,485	70% of total in Zone 2 (BBOWT)
Living landscape	East Berkshire	No	4,665	3,126	9,691	23,327	20% of total in Zone 2 (BBOWT)
Living landscape	Upper Thames	No	1,570	386	1,851	2,243	70% of total in Zone 2 (BBOWT)
Living landscape	West Berkshire	No	1,895	829	2,371	2,708	70% of total in Zone 2 (BBOWT)
Landcover type	Broadleaved Woodland	Low	10,520	19,569	33,755	52,601	20% of total in Zone 2 (CEH, 2016)
Landcover type	Neutral Grassland	Low	826	925	3,497	4,128	20% of total in Zone 2 (CEH, 2016)
Landcover type	Calcareous Grassland	Low	298	329	739	1,490	20% of total in Zone 2 (CEH, 2016)
Landcover type	Acid grassland	Low	0.2	0.2	293	1.2	20% of total in Zone 2 (CEH, 2016)
Landcover type	Heather	Low	38	90	157	192	20% of total in Zone 2 (CEH, 2016)
Landcover type	Heather grassland	Low	66	274	309	329	20% of total in Zone 2 (CEH, 2016)
Landcover type	Freshwater	Low	1,172	2,039	4,504	5,860	20% of total in Zone 2 (CEH, 2016)
Potential habitat	Network Lowland heathland	High	6,211	1,679	6,214	7,764	80% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Lowland meadows	High	34,582	4,164	34,612	43,228	80% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Lowland dry acid grassland	High	1,468	198	1,469	1,836	80% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Lowland calcareous grassland	High	10,406	1,551	10,408	13,008	80% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Lowland fens	High	3,318	340	3,324	4,148	80% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Purple moor grass & rush pastures	Low	60	9	99	302	20% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Reedbeds	Low	36	22	82	182	20% of total in Zone 2 (Edwards et al, 2020)
Potential habitat	Network Deciduous woodland	Medium	33,254	1,507	33,308	66,509	50% of total in Zone 2 (Edwards et al, 2020)
Urban greenspace	Milton Keynes	No	1	738	4,958	19,467	1 ha in Zone 2
Urban greenspace	Aylesbury	No	1	1,077	6,130	26,106	1 ha in Zone 2
Urban greenspace	Bicester	No	1	1,776	12,107	29,413	1 ha in Zone 2
Urban greenspace	Oxford	No	1	3,095	12,528	25,714	1 ha in Zone 2

Urban greenspace	Banbury	No	1	132	3,230	18,476	1 ha in Zone 2
Urban greenspace	High Wycombe	No	1	2,412	12,880	25,705	1 ha in Zone 2
Urban greenspace	Abingdon on Thames	No	1	1,272	8,354	25,948	1 ha in Zone 2
Urban greenspace	Slough	No	1	3,197	9,297	18,417	1 ha in Zone 2
Urban greenspace	Maidenhead	No	1	2,825	9,360	23,766	1 ha in Zone 2
Urban greenspace	Bracknell	No	1	4,005	10,212	20,252	1 ha in Zone 2
Urban greenspace	Reading	No	1	2,381	11,391	23,107	1 ha in Zone 2
Urban greenspace	Newbury	No	1	3,235	9,848	20,373	1 ha in Zone 2
Urban greenspace	Thatcham	No	1	3,723	11,353	20,320	1 ha in Zone 2

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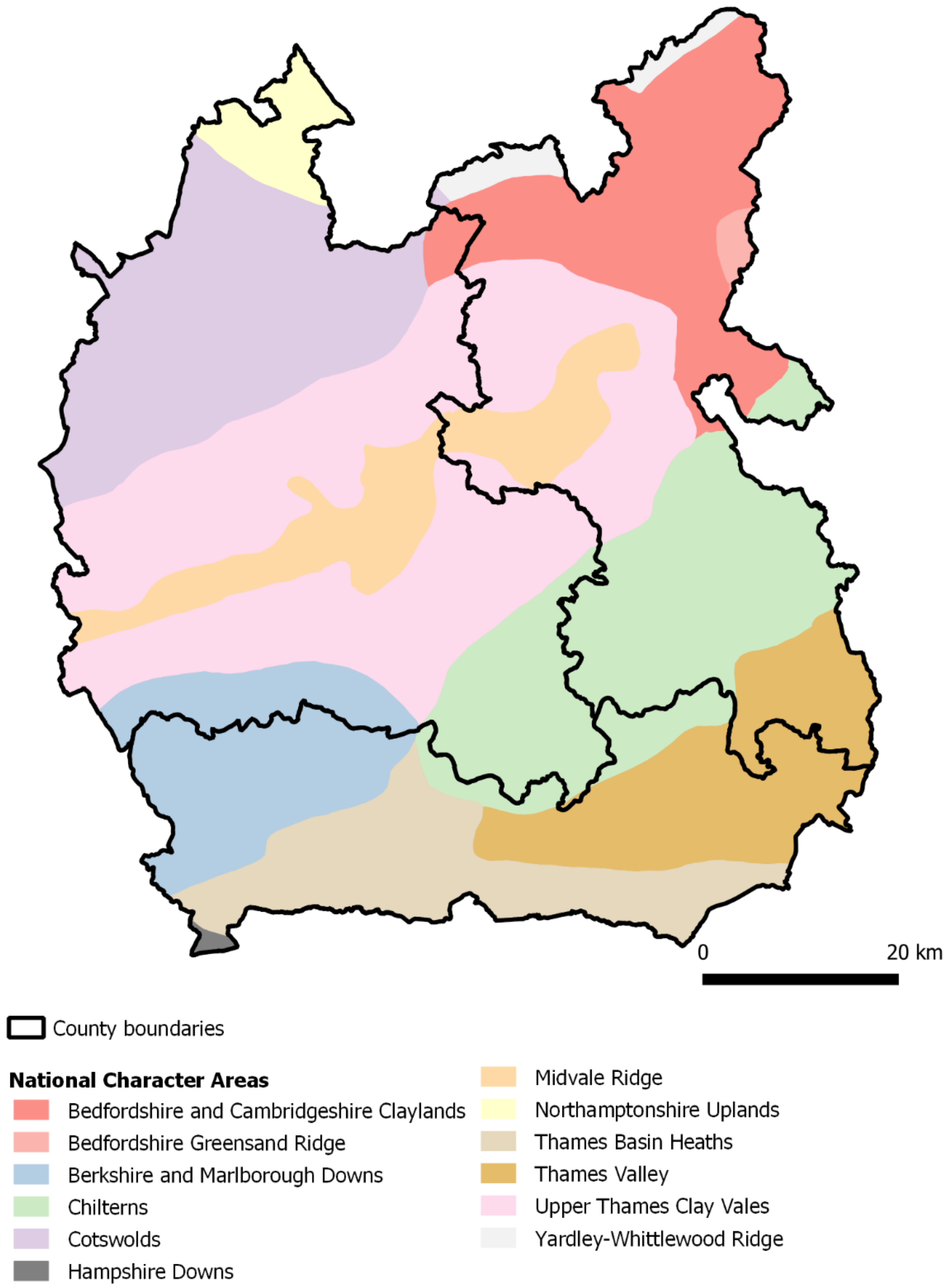
Figure S1: National Character Areas found within Berkshire, Buckinghamshire and Oxfordshire, each of which is a distinct biogeographical zone or ecoregion that is relatively homogenous in terms of the underlying geology and biodiversity (Natural England, 2014).



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