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Spatially targeting national-scale afforestation for multiple ecosystem services

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ABSTRACT

The potential for large-scale afforestation, as a climate change mitigation strategy, has led to national afforestation targets being proposed. These targets raise many questions, including how to optimise carbon storage, whilst enhancing other ecosystem services (ES). Here, we assess how decision-making at different scales might affect the spatial distribution of new tree planting in England and hence ES provision. This was achieved by modelling the impact of afforestation on three example ES (carbon sequestration, recreation, and flood mitigation) to identify the best areas for planting at five scales of decision-making: national, regional, county, district, and parish. The modelling shows that carbon sequestration rates are relatively invariant across England (once unsuitable areas are excluded), whilst recreation and flood mitigation are more spatially variable, so full simultaneous optimisation of the three ES is not possible. Consequently, recreation and flood mitigation are also more impacted by changes in planning-scale than carbon, with the modelling showing over 200% difference between the parish and national-scenarios for flood mitigation benefits. Overall, targeted afforestation at national scale maximises ES benefits, but risks overwhelming some landscapes with trees. Targeting afforestation using smaller planning units generates more evenly distributed planting, but lower ES benefits. Our results show national-scale planning produces over 35% more combined ecosystem value than planning at parish-scale, and over 65% more than randomized planting. This highlights the benefits of targeting at a relevant scale, but also the potential trade-offs between widely-distributed new tree planting (e.g., parish-scenario), versus planting to optimise ES provision (e.g., the national-scenario). These results do not imply a single 'correct' scale for planning, but instead highlight the importance of considering the impact of a specific scale on the different ES, and that even spatial targeting at the smallest scale produces higher ES benefits than random planting.

1. Introduction

It is becoming increasingly clear that rapid, large-scale action is required to reduce the risks related to global climate change (Rockström et al., 2017). Increasing carbon sequestration and storage, through afforestation and reforestation has the potential to be amongst our most effective natural climate solutions (Bastin et al., 2019; Lewis et al., 2019). Consequently, recent years have seen numerous initiatives aimed at encouraging tree planting at both the international (IUCN, 2020; United Nations, 2015) and national scales (Andrasevits et al., 2005; Palaghianu, 2015). In addition to carbon sequestration through tree growth, and storage in tree biomass, litter and soil (Cannell & Milne, 1995; Dewar, 1990), forests have the potential to provide a range of ecosystem services (Lake et al., 2020), including recreation and flood mitigation.

There is increasing recognition of the positive impact woodland recreation can have on wellbeing, with trees being linked to improvements in both physical and psychological health (Bell & Ward Thompson, 2014; Goodenough & Waite, 2020). Mature forested catchments have also been shown to provide higher evaporative losses and reduce the peak flows associated with smaller storms compared with grassland (Dadson et al., 2017). With studies highlighting the contribution of greenhouse gas emissions to flooding (Pall et al., 2011) and extreme precipitation events (Christidis et al., 2021; Dadson et al., 2017), the issue of flood mitigation is of increasing importance. The degree to which these ecosystem services are provided depends on the location, extent, configuration, and condition of the woodland from which they originate (Philips, 2017). The spatial distribution of ecosystem service

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provision is therefore heterogeneous, and woodland in one location will not necessarily provide the same benefits as another, even if it has similar characteristics (Gimona & van Der Horst, 2007). Spatially targeted planting could therefore ensure that preferred environmental and societal benefits are gained from large-scale afforestation efforts.

Recognising this spatial variability, various approaches have been adopted in recent years to synthesise the results of multiple ecosystem service assessments (Cortinovis et al., 2021), and identify ‘hotspots’ or spatial prioritization areas (Moilanen et al., 2022; Runge et al., 2016), where provision is highest, primarily for the purposes of conservation (Cimon-Morin et al., 2013). Hotspots can be defined both as key areas that provide more than one ecosystem service, or a large proportion of one individual service (Egoh et al., 2008; Cimon-Morin et al., 2013). Hotspot selection methods range from the richest cell approach, where locations with the highest values are chosen, to measures of spatial clustering, counts of the number of services in an area to give a measure of diversity, or the use of heuristic optimisation algorithms (Cortinovis et al., 2021; Schröter & Remme, 2016).

Research on multiple ecosystem services has often focussed on mapping the current provision of different services to explore and understand the synergies and trade-offs between them (Egoh et al., 2008; Hou et al., 2018; Wu et al., 2013). However, studies are increasingly modelling ecosystem service provision under a range of future land use scenarios to inform decision-making and often to identify the most beneficial areas for a particular management action/intervention (e.g. afforestation, saltmarsh reclamation, habitat restoration) (Crossman & Bryan, 2009; Davis et al., 2019; Finch et al., 2021; Gimona & van Der Horst, 2007). Modelling the ecosystem-service outcomes of future land-use scenarios/interventions has largely been carried out at local and regional scales, but at a national scale has the potential to be a valuable tool in planning for the implementation of emerging national-scale afforestation targets. This approach could allow for levels of ecosystem service provision from hypothetical new woodland to be determined, and the optimal location for desired services chosen, ensuring that benefits are maximised from large-scale afforestation efforts, such as those being proposed for carbon sequestration purposes.

Planning for large-scale afforestation can take place in a variety of systems, and at a range of spatial scales (Burke et al., 2021; Lawrence & Ambrose-Oji, 2015). In the United Kingdom, a centralised, ‘top-down’ approach was seen during the first half of the 20th century, driven by the purchase and afforestation of vast areas of cheap, marginal quality land by the state (Nail, 2008). More recently, there has been a shift to private woodland creation and ownership, both in the United Kingdom (Hopkins et al., 2017) and more widely (Palaghianu & Dutca, 2017; Vadell et al., 2016), with landowners being encouraged to plant within their land through grant payments or similar systems.

Afforestation targets have been proposed by a wide range of stakeholders, for a wide-range of scales from highly localised planting (Wirral Borough Council, 2020), through city-level (Lancaster City Council, 2019; McPhearson et al., 2017) up to country (Thomson et al., 2018) and global-level (Lewis et al., 2019). In some cases, the targets have clear plans about how and where planting will occur, but for others there is considerable uncertainty about both the type of planting (plantation or natural restoration) and the location of the new woodland (Lewis et al., 2019). The range of scales covered by these targets and the number of organisations involved means that afforestation planning will be undertaken at a range of planning scales.

Typically, land-use planning occurs at different scales, due to the different levels of administration and decision-making, and the diverse group of stakeholders involved, including government departments and private organisations (Hauck et al., 2016). In the UK, the main planning scales include national government, regional bodies, county councils and parish councils, with equivalent hierarchical systems found in many other countries (e.g., Hautdidier, 2011). Different scales of decision-making are important because spatial scale affects the optimisation of land-use planning, due to the spatial variability of ecosystem service provision (Scholes et al., 2013). Planning across larger areas provides more opportunities to optimise ecosystem service provision, but may lead to spatially uneven service provision (Pohjanmies et al., 2017; Raudsepp-Hearne & Peterson, 2016). Planning scale may affect ecosystem service quantification, and hence the decisions drawn, even if the management objectives remain the same (Pohjanmies et al., 2017). Quantification of ecosystem services at different spatial resolutions may impact perceived patterns of provision and the relationships between services in a range of contexts (Anderson et al., 2009; Burke et al., 2020; Hou et al., 2018; Raudsepp-Hearne & Peterson, 2016). The quantification of ecosystem services at a constant spatial resolution, but within differing planning scales is less well explored, but has also been shown to affect the identification of ecosystem service hotspots (Blumstein & Thompson, 2015), measured correlations between services (Sun et al., 2020), and the relationship between biodiversity and ecosystem services (Anderson et al., 2009). A multi-scale ecosystem services-based approach could therefore provide a valuable framework for planning large-scale afforestation.

Recently, large-scale afforestation in the UK has been proposed for climate mitigation (Burke et al., 2020; Thomson et al., 2018). This raises questions about how to plant new trees to optimise carbon (Baggio-Compagnucci et al., 2022; Bradfer-Lawrence et al., 2021), but also about how to distribute new woodland to enhance other ecosystem services. The aim of this study was therefore to determine the effectiveness of optimizing the provision of multiple ecosystem services to spatially target a national-scale programme of afforestation. This was achieved by: (i) modelling the consequences of afforestation for the provision of three example ecosystem services (carbon sequestration, recreation, and flood mitigation), in a spatially-explicit manner for the whole of England; (ii) using outputs from the three individual ecosystem services to map the provision of combined ecosystem services that would be delivered by afforestation across the country; (iii) identifying hotspots where afforestation could optimise the delivery of multiple ecosystem services, while meeting the national afforestation target; (iv) determining the effects on ecosystem service delivery of planning targeted afforestation at different scales of decision-making, according to national, regional, county, district and parish administrative boundaries, alongside randomly distributed afforestation for comparison.

2. Methods

2.1. Case study and study area

To demonstrate the use of an ecosystem services-based approach to large-scale afforestation planning, England was used as a case study. As part of the United Kingdom, England has seen substantial planting in recent history (Aldhous, 1997), but remains amongst the least wooded countries in Europe (FAO, 2020). Recent years have seen a range of proposals aimed at increasing woodland area in the UK, primarily for the purposes of carbon sequestration and storage (Burke et al., 2021).

In this case study, we use the example of the *medium ambition* scenario proposed by the UK Climate Change Committee (Committee on Climate Change, 2018; Thomson et al., 2018), an independent statutory body formed to advise the UK government on climate change mitigation and greenhouse gas emission reduction. This medium ambition scenario outlines a suite of measures intended to reduce greenhouse gas emissions from the Land Use, Land Use Change and Forestry sectors, assuming reasonable uptake of currently available technologies (Thomson et al., 2018). Amongst these is a proposal to plant 10,000 ha of new woodland in England each year until 2100, resulting in the creation of approximately 840,000 ha of new woodland. While primarily intended to facilitate carbon sequestration and storage, this large-scale new tree planting offers an opportunity to provide a range of additional ecosystem services, if planned appropriately.

2.2. Modelling of ecosystem services

The potential provision of ecosystem services from new woodland creation in England was modelled in a spatially explicit manner (Fig. 1) using three services as examples (Fig. 2). As climate change mitigation is the primary aim of many proposed tree-planting schemes, carbon sequestration was selected as one of these. In addition to this, recreation, and flood mitigation were also selected, as these woodland services are of increasing importance. While three services were modelled here, future work could involve the use of additional or different services, should appropriate data be available. For each of the services, modelling was carried out for the whole of England at a spatial resolution of 1 km^2. As in comparable studies (Davis et al., 2019; Finch et al., 2021; Hou et al., 2018), we used a combination of existing predictive ecosystem service models and custom measures derived from spatial data, to create layers showing potential ecosystem service provision from new woodland.

2.2.1. Carbon sequestration

A spatial dataset quantifying the potential for carbon sequestration was calculated using existing models and data, with a methodology comparable to that previously used to estimate timber production and carbon sequestration in the UK (Finch et al., 2021; Haw, 2017). Specifically, a two-stage method was applied, where yield classes were estimated first and then converted to carbon sequestration rates. The Forest Research Ecological Site Classification (ESC) model (Bathgate, 2011) was first used to predict the yield class of woodland established within each grid cell of the study area. Yield class is an index used to describe forest productivity, based on the maximum mean annual increment of cumulative timber volume achieved by a tree species under

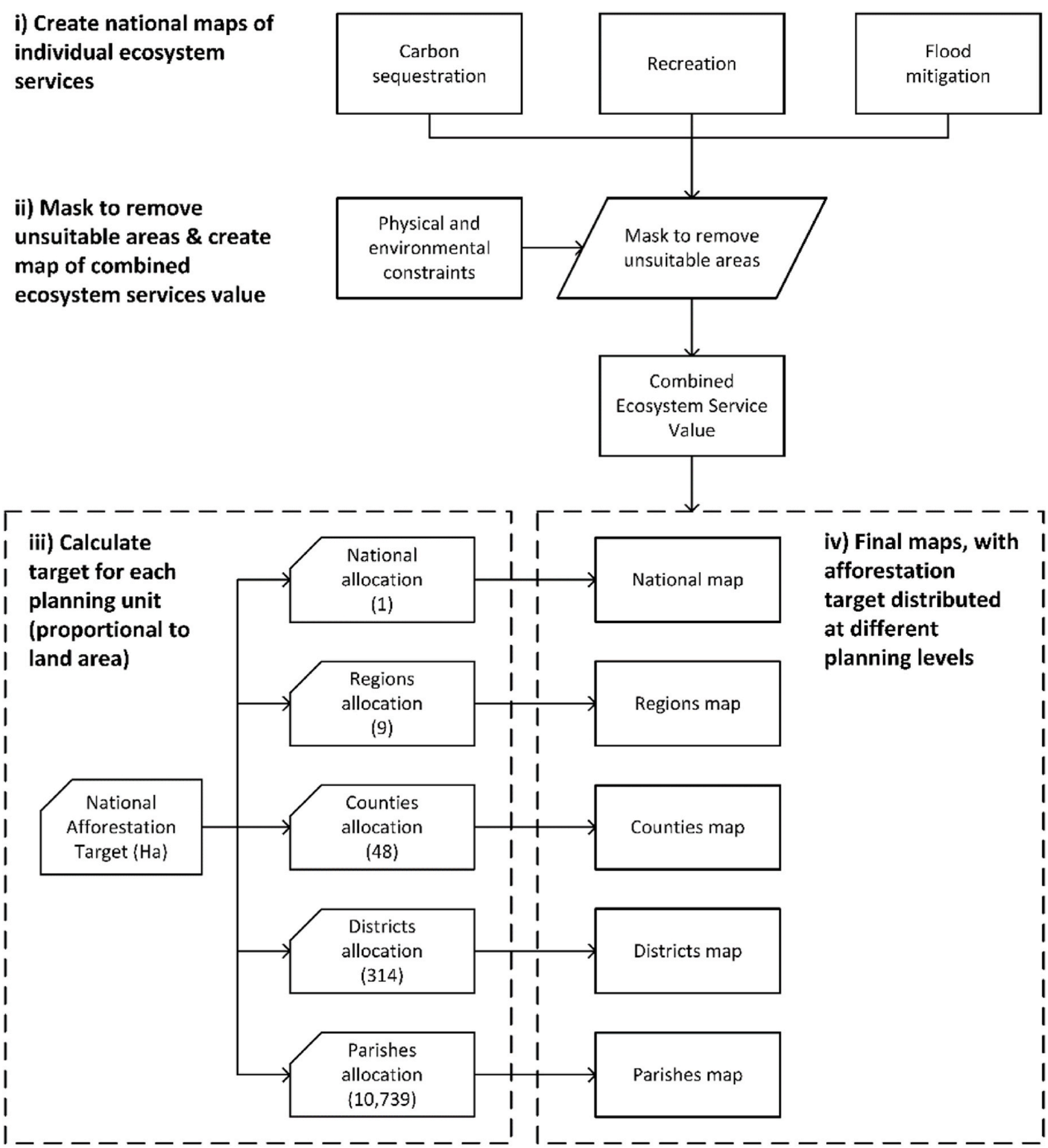

Fig. 1. Overview of the modelling framework showing how the datasets are created and combined, before new planting areas are allocated at different planning levels. Values in brackets represent the number of planning units at each level, e.g., 9 planning units at regional level.

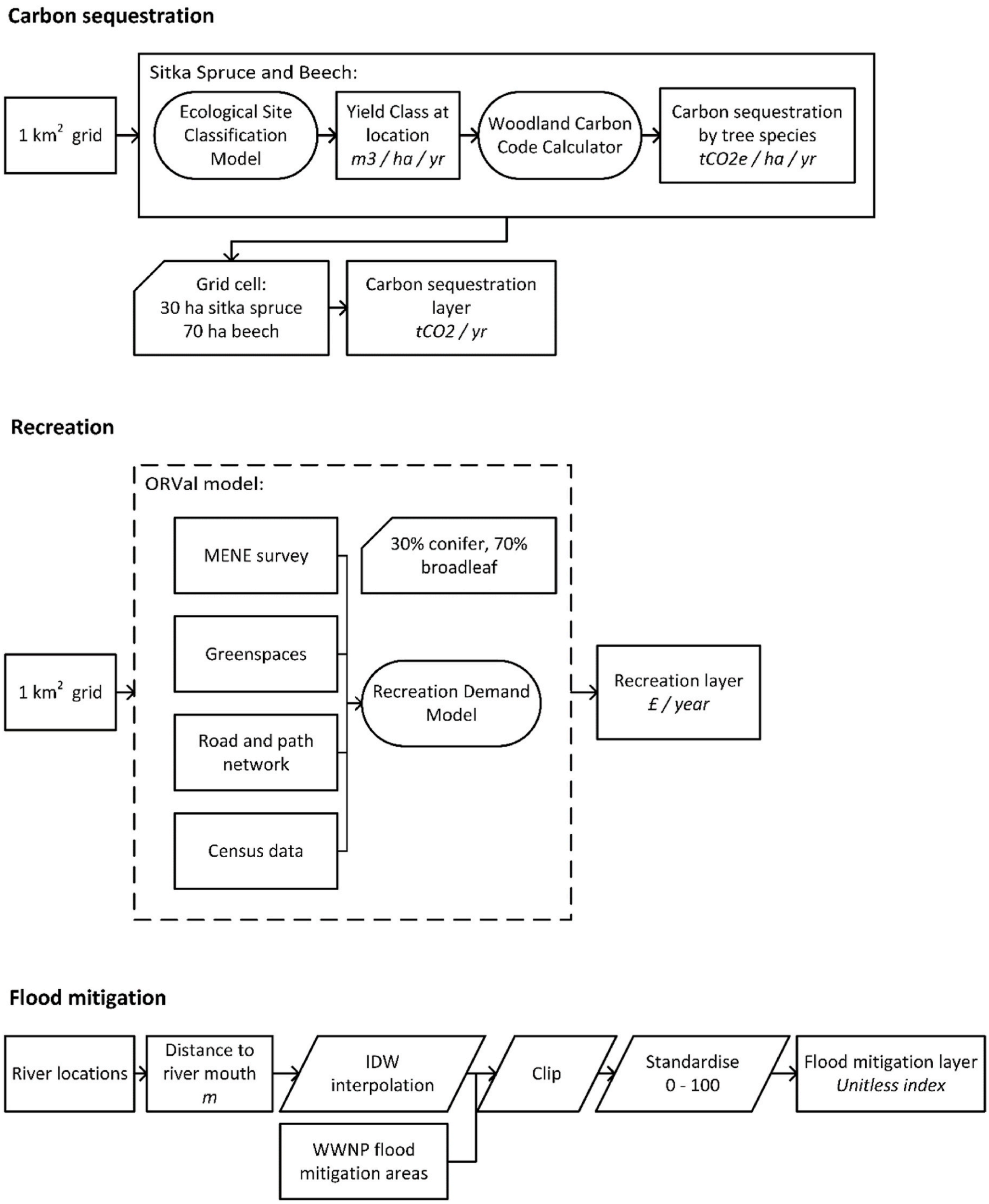

Fig. 2. Overview of the creation of the three ecosystem service layers.

specified conditions, measured in cubic metres per hectare per year (Mathews et al., 2016). The ESC model uses climate characteristics (accumulated temperature, continentality, aspect and moisture deficit) and soil characteristics (moisture regime and nutrient regime) to assess the suitability of a site for the growth of a given tree species, including a prediction of its maximum potential yield class (Bathgate, 2011). The model was run for each grid cell in the study area, for both Sitka Spruce (the representative coniferous species) and Beech (the representative broadleaf species). The result was two layers identifying the maximum potential yield class of both species across England (Appendix A, Fig A1).

Lookup tables were used to convert yield class to rates of carbon sequestration (Randle & Jenkins, 2011). The lookup tables provide rates of carbon sequestration per hectare for a given tree species of a given yield class, under a specific management regime. As in the UK Climate Change Committee medium ambition scenario, we assume planting with a spacing of 1.2 m for Beech and 2 m for Sitka Spruce (Thomson et al., 2018). As rates of carbon sequestration vary with a tree's age, we calculated the average carbon sequestration over the first 100 years of growth, and assumed that no thinning has occurred. Carbon sequestration values for a range of even numbered yield classes are given in the lookup tables used. Yield classes outside this range, and odd numbered yield classes, were interpolated using a simple straight-line fit (Appendix A, Fig A2, Fig A3). Annual rates of carbon sequestration were then calculated for each grid cell, assuming each cell was planted with 70 ha of Beech and 30 ha of Sitka Spruce.

2.2.2. Recreation

Potential for recreation was calculated using the ORVal model (Day & Smith, 2016). This is a statistical recreational demand model that allows visitation and monetary welfare values to be generated for existing and hypothetical new greenspaces at specified sites (Day & Smith, 2017). It has previously been used in a variety of studies to estimate the recreational value of existing sites (Clark, 2017; Day et al., 2018), and to predict future provision under potential land use scenarios (Davis et al., 2019; Finch et al., 2021).

The model was used to estimate the monetary welfare value of a new woodland site created at the centre of each grid cell in the study area. Each site was defined as 1 km^2 in area, and composed of 70% broadleaf woodland and 30% coniferous woodland.

2.2.3. Flood mitigation

Calculation of flood mitigation potential was based largely on Environment Agency data that identifies potential areas for Working with Natural Processes (WWNP), also known as Natural Flood Management (Hankin et al., 2017) across England. This dataset identifies areas where tree planting has the potential to mitigate flood risk, including flood plains, riparian zones, and on slowly permeable soils, with trees slowing overland flow, enhancing canopy evaporation, increasing floodwater storage, and dissipating flood energy.

The Environment Agency WWNP dataset is categorical, with two classes: areas that could provide a flood mitigation benefit if planted, and areas that could not. To generate a continuous dataset, with high values for the most important areas and low values for the least important areas, the dataset was extended by calculating distance to river mouth for sections of river in locations where planting could provide a benefit. Modelling suggests that forest restoration in distal headwaters, far from the river mouth, is effective at reducing peak flood discharged, compared with restoration near the catchment outflow, which can increase peak magnitude (Dixon et al., 2016). The final dataset was normalised with values ranging from 0 (no benefit) to 100 (maximum benefit) with an average value calculated for each 1 km^2 grid cell. Further details of the method are presented in Appendix B.

2.3. Removal of unsuitable areas

Tree planting is not possible, or suitable, in all areas. Physical and environmental constraints on afforestation were identified using constraint maps produced in Burke et al. (2021). Physical constraints include areas where large-scale tree planting is not physically feasible such as existing woodland, water, rock and coastal sediment, above the climatic treeline, and urban and suburban areas. Environmental constraints identify areas of peat and bog. Afforestation in these areas can lead to net CO_2 emissions. Cells where over half the land was covered by these physical and environmental constraints were designated as being unavailable for planting, and were removed from the analysis.

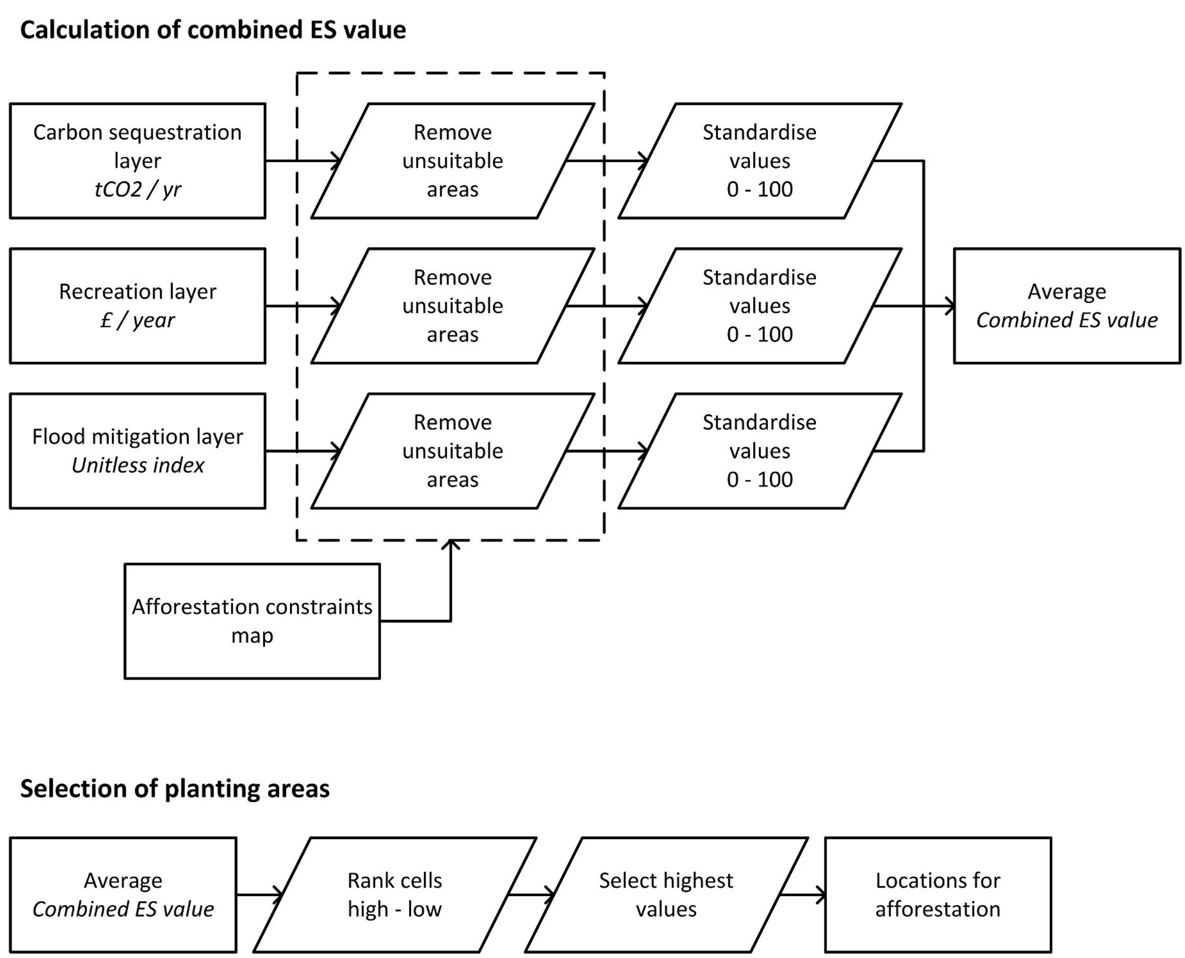

Fig. 3. Combination of the three ecosystem service layers using an ‘intensity’ approach to determine CESV ranking of cells per planning unit to determine locations for afforestation.

2.4. Quantifying the provision of multiple ecosystem services

Areas where afforestation could deliver multiple ecosystem services were identified using an 'intensity' approach, widely used in studies of multiple ecosystem services (Cortinovis et al., 2021; Schröter & Remme, 2016) (Fig. 3). Each ecosystem service provision layer was first normalised such that its values lay between 0 and 100 using Equation (1):

$$x_{norm} = \frac{x - \min(x)}{\max(x) - \min(x)} \times 100 \qquad \text{(Equation 1)}$$

For each cell, the mean level of ecosystem service provision from the three services modelled was then calculated, resulting in a combined ecosystem services value (CESV). In this instance, all three services were assigned equal weights, although future work could assign weights to prioritise specific ecosystem services (Section 4.3). Following a richest cells approach (Schröter & Remme, 2016), these CESVs were then ranked from high to low, and the top ranked cells selected for planting for the chosen planning unit (Fig. 3).

2.5. Assessing the impact of planning scale on the provision of ecosystem services

Five scenarios were constructed, with planting locations being identified within different administrative boundaries in order to explore the use of an ecosystem services-based approach to afforestation planning at differing scales. The first, the *national* planting scenario, is analogous to a large-scale centrally administered planting scheme. It maximises the provision of multiple ecosystem services from new woodland at the national scale by selecting the 8,400 1 km^2 cells containing the highest CESVs from across the whole of England, thus identifying 840,000 ha of land for afforestation, as proposed in the *medium ambition* planting target.

Subsequent scenarios were constructed using the administrative boundaries from a hierarchy of decision-making scales from regions, counties, districts and parishes (Table 1). At each scale, the administrative boundaries defined the extent of (multiple) individual planning units. In these scenarios, it is assumed that each planning unit plants a proportion of the national afforestation target relative to its land area, analogous to a planting scheme devolved to local authorities and communities. For example, in the *districts* scenario, Lancaster district has a land area of 57,621 ha, making up approximately 0.44% of the land area of England. In this scenario, it would therefore plant 0.44% of the national 840,000 ha planting target, equal to 3,710 ha. Following the approach used in the *national* planting scenario, cells within Lancaster district were first ranked by their CESVs from high to low, and the top 37 selected, identifying the approximately 3,700 ha of land required for afforestation. This process was repeated for each district in England, resulting in approximately 840,000 ha of land being identified for afforestation.

The current spatial distribution of woodland in England is highly uneven. These regional to parish scale scenarios therefore evaluate an approach where planting is more evenly distributed across the country, and ensures no single area is overwhelmed by new woodland. It also allows the impact of planning targeted afforestation at different scales of decision-making to be explored, from national government, to local parishes. These scenarios were compared with a *random* planting scenario, where grid cells were selected from across England at random for planting, to simulate untargeted woodland creation.

Table 1
Planning units used in construction of the planting scenarios.

Planning Region	Count	Land Area (ha)		
		Average	Largest	Smallest
National	1	13,046,148	13,046,148	13,046,148
Regions	9	1,449,563	2,385,107	157,351
Counties	48	271,793	865,697	290
Districts	314	41,548	502,617	290
Parishes	10,739	1,215	25,556	0.038

3. Results

3.1. Spatial variability of ecosystem service provision

Each of the three ecosystem services modelled have substantial spatial variability and varying levels of provision (Fig. 4). Potential rates of carbon sequestration range from 111 $tCO_2e/km^2/a$ (units are tonnes (t) of carbon dioxide (CO_2) equivalent (e) per km^2 per year) in the least productive areas, to 1,497 $tCO_2e/km^2/a$ in the most. Potential welfare values from recreation were more variable, ranging from £3,614/km^2/a to £1,685,796/km^2/a. As flood mitigation potential was calculated as a normalised index, values ranged from 0 where planting is deemed to have no positive impact on flood mitigation, to 1 where it is deemed to have the most.

Rates of carbon sequestration were highest in the west of the country, due to more favourable climatic conditions resulting in increased tree growth, whereas welfare values for new woodland recreation sites were highest near urban areas, and the people to benefit from recreation. Whilst not all land has flood mitigation potential, the areas with flood mitigation potential from afforestation were distributed across all regions. No spatial correlation between the three services was found using Spearman's correlation coefficients (Appendix C).

Normalising the grid cells in each of the three ecosystem service maps to lie between 0 and 100, then combining them with an equal weighting, results in a map of CESV (Fig. 5). This varied from 0.34 to 69.3, demonstrating that while afforestation in all available locations within the study area (i.e. excluding areas masked out due to physical and environmental constraints) would provide ecosystem services, even if to a very small degree, no singular location is optimal for all three ecosystem services studied here (as this would result in a CESV of 100). Fig. 5 also shows existing areas of woodland (most woodlands in England are small, so only the largest areas are visible), which shows that the areas with the highest combined ES values do not particularly correspond to the largest current areas of forest.

3.2. Planting scenarios

From this map of combined ecosystem services value, five hypothetical planting scenarios were developed, using planning units of differing spatial scales (Fig. 6). Each planning unit leads to a differing proposed planting distribution. The *national* scenario, where the national tree planting target is distributed across the whole of England, results in large concentrated areas of afforestation, especially in the north, west-midlands and south (Fig. 6a) whereas the *regions* and *counties* scenarios, where the national target is distributed proportionally across each region and county, bring more planting to the east of England (Fig. 6b and c). The *districts* scenario (Fig. 6d) results in smaller patches of more widely distributed planting, with the larger continuous areas of new afforestation, seen in the national-scale modelling, largely gone. Meanwhile, the *parishes* and *random* scenarios (Fig. 6e and f) both display mostly singular cells of new planting, distributed throughout the study area.

These differing patterns of planting result in different levels of combined ecosystem service provision. Planting according to the *national* scenario would result in the highest overall level of provision, with a mean CESV of 40.5. This mean value decreases as the planning unit, within which locations for planting are identified, decreases in size (Table 2, Table 3). All planned scenarios are significantly higher than the untargeted woodland creation in the *random* scenario, with a mean CESV of 24.2 (Appendix D). The national scenario could generate up to 67% more ecosystem service provision than the random (untargeted) scenario.

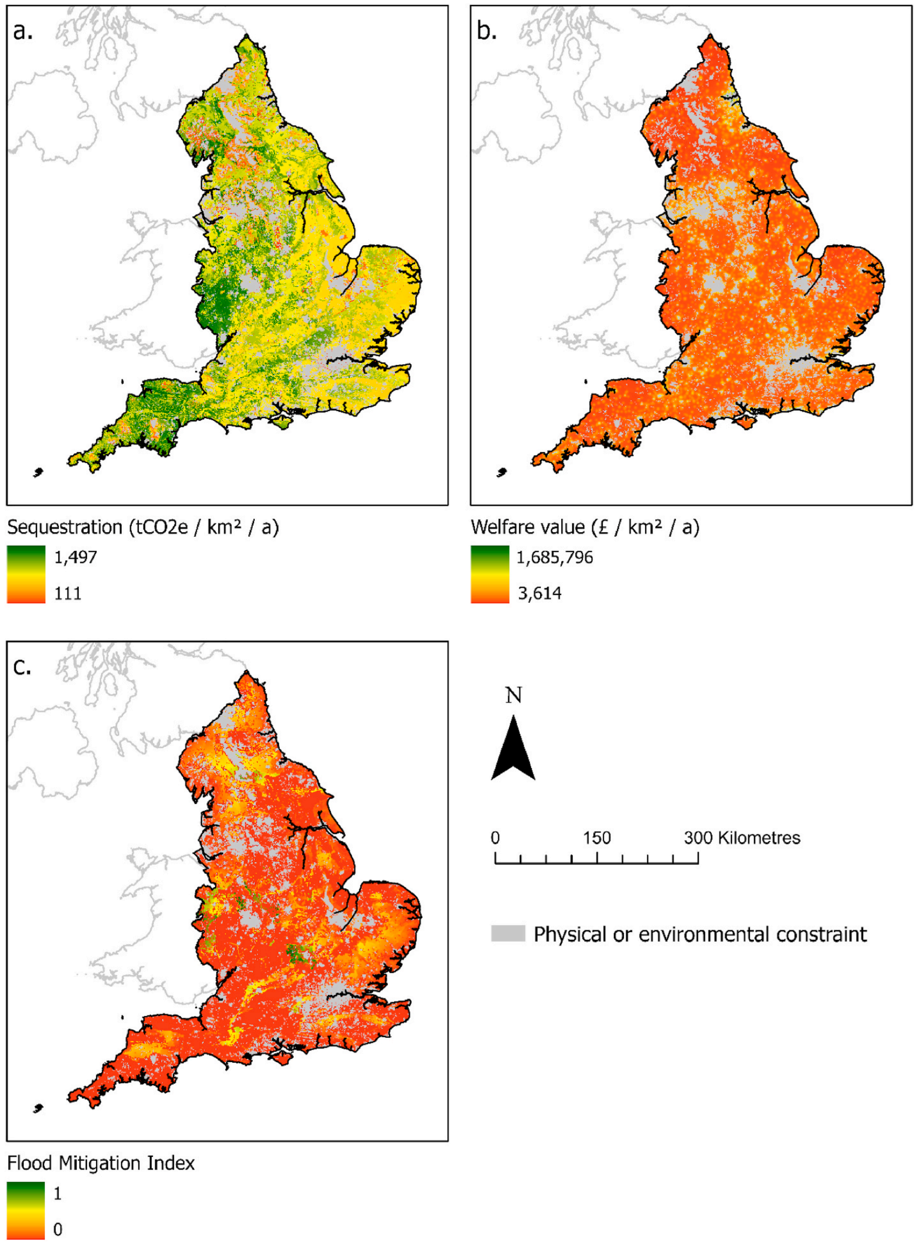

Fig. 4. Distribution of ecosystem service provision from potential new woodland for a) carbon sequestration b) recreation and c) flood mitigation.

The use of larger planning units is more efficient for carbon sequestration and flood mitigation as the larger planning units result in higher values (Fig. 7, Table 2, Table 3). Conversely, smaller planning units, with the exception of the *parish* planting scenario, while having lower values for overall intensity, result in a slightly higher value for recreation, possibly due to increased planting close to population centres. Values for carbon sequestration are comparatively high in all scenarios, suggesting spatial targeting for this service is less important compared with recreation and flood mitigation. The number of cells selected in the *parish* scenario (7,820) is less than the target of 8,400 (equal to 840,000 ha), because the amount of planting assigned to some parishes was less than 1 km^2, so no cells were selected. Additionally, some parishes did not contain enough available land to make up the required number of cells.

3.3. Distribution and size of afforestation

The amount of planting being considered in the medium ambition scenario (Thomson et al., 2018) is substantial. With a current woodland area in England of 1,308,000 ha (Forest Research, 2019), the 840,000 ha of new planting proposed is equal to an increase of over 60%.

Of the 314 districts in England, 11 were identified as having no land available for planting. Of these, 10 were highly urbanised London boroughs where all cells were deemed unsuitable for planting when land with physical and environmental constraints was removed (Section 2.3). The other is the Isles of Scilly, where no data was available for the ESC model used in production of the carbon sequestration layer (Section 2.2.1).

Of the remaining districts with available space, all would receive some new planting under the *districts* planting scenario. Under the *national* planting scenario however, 92 would receive no planting, while 10 would receive over 25% of their land areas as new woodland. Similarly, planning afforestation within larger planning units, such as in the *national, counties* and *districts* scenarios, results in the creation of large, continuous areas of new woodland, on the scale of, and in some cases exceeding, the largest existing woodland areas in England (Table 4).

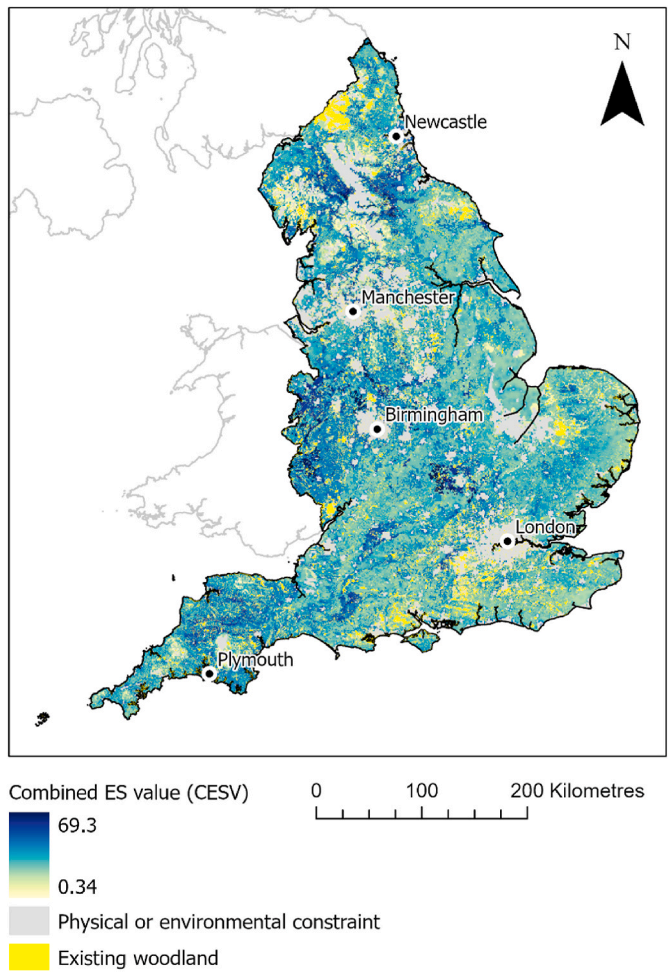

Fig. 5. Model estimates of potential CESV from new woodland planting, alongside existing woodland distribution.

4. Discussion

4.1. Impact of planning scale on ecosystem service provision and distribution

Given a national afforestation target, we show that identifying areas to prioritise for planting, within larger planning units, provides greater potential benefits than planning within small units. This is because smaller units are less efficient for selecting sites that optimise delivery of multiple ecosystem services. These national-scale results support previous regional and landscape-scale results that have highlighted the greater ability of larger planning units to optimise land-use decisions for multiple ecosystem services (Pohjanmies et al., 2017; Raudsepp-Hearne & Peterson, 2016). Our work also demonstrates that spatial targeting, even within smaller spatial units, provides significantly greater benefits compared with random, untargeted planting. This highlights the importance of considering the spatial distribution of multiple ecosystem services, even in local scale planting projects, which may better fit with local priorities, funding and needs (Agbenyega et al., 2009; Burton et al., 2019).

Our results support previous work mapping multiple ecosystem services, in finding that while hotspots do exist, levels of congruence between different ecosystem services are generally poor (Egoh et al., 2008; Hou et al., 2018; Wu et al., 2013), but that larger planning units enable the trade-offs between different ecosystem services to be balanced more effectively (Pohjanmies et al., 2017). This is because the three services modelled here have different spatial distributions, so they have different interactions with the planning scale (Raudsepp-Hearne & Peterson, 2016). Potential for carbon sequestration for example is high across much of the study area, and as such, it is high for all of the planning scales (Table 3). Areas with high potential for flood mitigation on the other hand are generally confined to inland locations. Potential flood mitigation benefits are therefore lower when afforestation is constrained by smaller spatial units, as more planting is allocated to coastal areas, suggesting that planning within larger areas is required to optimise this service effectively.

Understanding the best scale (or scales) for afforestation planning is further complicated by the fact that ecosystem services may be the result of processes taking place at different scales (Kremen, 2005) and so may require multi-scale approaches (Scholes et al., 2013; Seppelt et al., 2013). Typically, afforestation takes place within political or economic subdivisions, such as local government authorities or privately owned land, whereas ecosystem service production and provision will cut across these boundaries. Likewise, there can be difference in the scale of ecosystem service provision and consumption and an offset in their respective locations. Carbon sequestration for example can be considered a “global” ecosystem service, with consumers receiving the same benefit regardless of their location relative to the woodland that provides it (Raudsepp-Hearne & Peterson, 2016), whereas recreation is more localized, with benefits being provided only to those in proximity to the trees from which the flows of benefits originate (Cimon-Morin et al., 2013). Flood mitigation is directional (Fisher et al., 2009), so trees planted for that purpose may only benefit those downstream of them. Overall, multi-scale analyses have a role to play in highlighting both the trade-offs between ecosystem services, but also the trade-offs between the scales at which the analysis and the decision-making are conducted. In practice, it is important to be clear about the ES benefits required from new tree planting to enable the appropriate scales to be considered and full ES provision to be achieved.

4.2. Spatial implications for afforestation schemes

Resources for afforestation are finite, and there are both costs and practical issues associated with the establishment of new woodland (Whittet et al., 2016). Planning for afforestation at the national scale, or within large spatial units, may therefore be most desirable in order to optimise ecosystem service benefits. Whereas schemes that confine planting only to specific areas, such as selected districts, counties or regions may be less likely to optimise ecosystem service benefits. However, plans developed at a large-scale may also result in a more uneven distribution of costs and benefits amongst stakeholders, which may hinder a plan’s acceptability (Raudsepp-Hearne & Peterson, 2016).

In our assessment, the *national* planning scenario results in larger continuous areas of planting, concentrated in a limited number of areas, compared with the more widely distributed planting seen with smaller spatial planning units (Table 4). Studies show people have a preference for between 25% and 50% forest cover in a landscape (van der Horst, 2006), so highly concentrated planting has the potential to have a negative impact on local communities, although higher resolution work would be needed to measure this at the landscape scale. Meanwhile, other areas would gain far less planting, and therefore fewer benefits. While England is used as a case study in this work, it may also be that planting elsewhere within the wider United Kingdom, or even globally, could provide greater benefits (Lewis et al., 2019).

4.3. Developing the method for different priorities

This paper primarily focusses on the spatial targeting of afforestation in order to optimise the provision of multiple ecosystem services. However, planting new trees involves a broad range of stakeholders, so optimizing ecosystem services is one of a number of criteria likely to influence planting decisions. Other criteria may include exploring how benefits from new planting can be shared amongst a population equally,

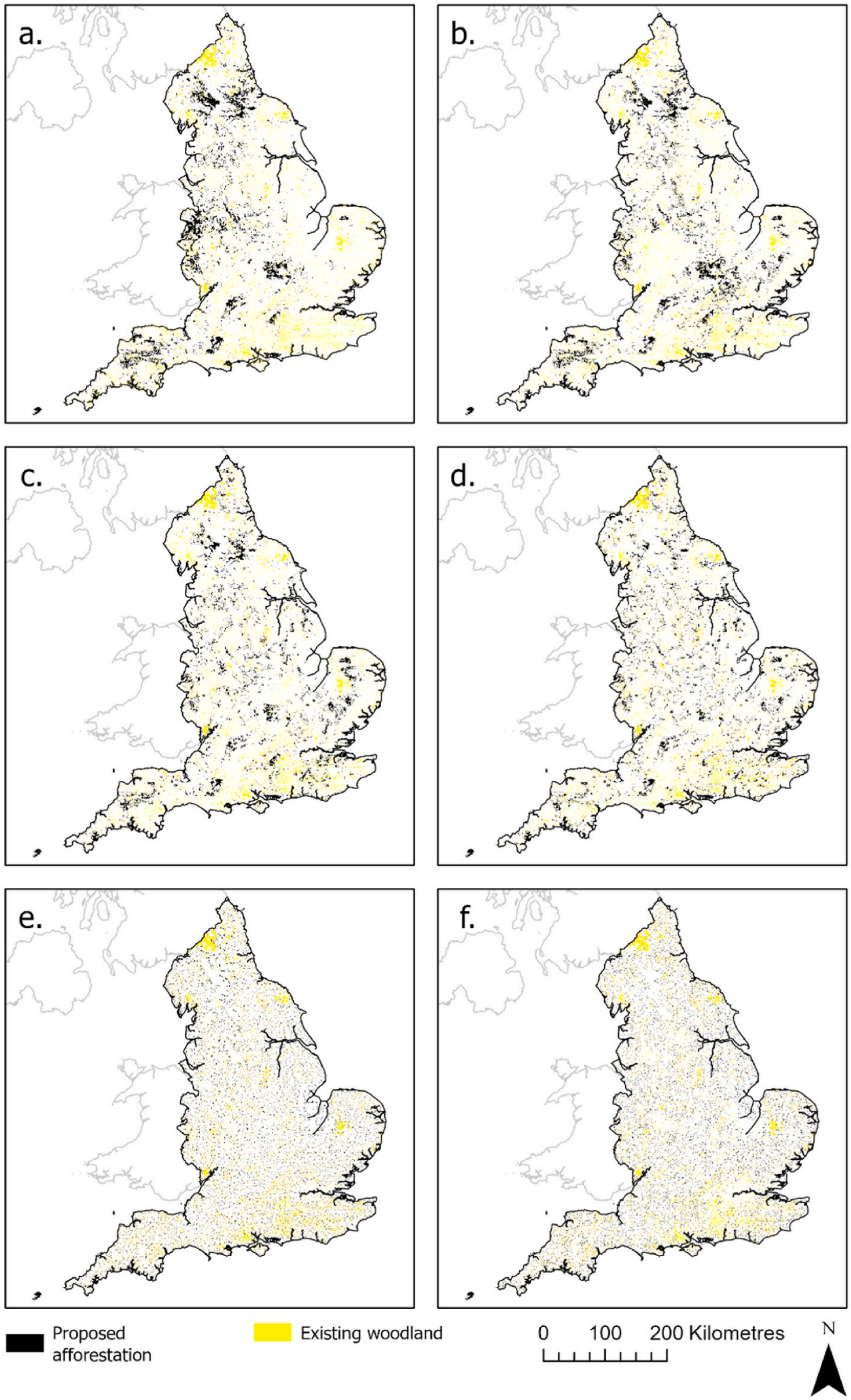

Fig. 6. Proposed patterns of afforestation from modelled scenarios for a) national b) regions c) counties d) districts e) parishes and f) random. Total proposed new planting in all scenarios is approximately 840,000 ha, as proposed in the Committee on Climate Change medium ambition scenario (Section 2).

or more equitably, and attempting to bring all areas up to a common level. Alternatively, decision-makers may choose to minimise losses from replaced land cover, both in terms of the monetary cost of land conversion, or by quantifying the value of services lost when land cover in replaced, in essence calculating the net, rather than gross, value of new afforestation (Davis et al., 2019). In evaluating an existing national subsidy-based planting scheme Gimona and van Der Horst (2007) found that existing approaches to spatial targeting of woodland creation were no better, or even worse, in terms of ecosystem service delivery than if the trees were planted randomly.

The method presented here applied equal weights, spatially and across the three ecosystem services, but the method could be adapted to model different priorities. So spatial weights could be applied to target particular areas, or weights could be applied to prioritise certain ecosystem services. Different approaches to targeting planting could also be explored. Here we have used a 'land-sharing' style approach,

Table 2
Ecosystem service provision in each of the modelled scenarios (normalised values).

		Combined ES Value			Carbon Sequestration			Recreation			Flood Mitigation		
Planning Scale	Cells Selected	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
National	8,400	40.5	34.8	68.9	72.2	1.2	100.0	12.2	0.19	100.0	37.2	0.0	100.0
Region	8,399	39.3	24.2	68.9	71.3	1.2	100.0	13.0	0.2	100.0	33.5	0.0	100.0
County	8,402	37.7	18.0	68.9	71.2	1.2	100.0	13.8	0.2	100.0	28.2	0.0	100.0
District	8,370	36.4	6.0	68.9	70.5	1.2	100.0	14.7	0.2	100.0	23.9	0.0	98.3
Parish	7,820	31.6	1.2	68.9	68.8	1.2	100.0	13.2	0.08	100.0	12.8	0.0	98.3
Random	8,400	24.2	1.0	61.6	56.4	1.2	98.9	9.2	0.0	72.0	6.9	0.0	95.9

Table 3
Ecosystem service provision in each of the modelled scenarios (raw values).

		Carbon Sequestration ($tCO_2/km^2/a$)			Recreation (£/km^2/a)			Flood Mitigation (0–100 normalised index)		
Planning Scale	Cells Selected	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
National	8,400	1,112.1	126.9	1,497.3	208,919.0	6,841.2	1,685,796.1	37.2	0.0	100.0
Region	8,399	1,099.7	126.9	1,497.3	222,967.0	7,436.8	1,685,796.1	33.5	0.0	100.0
County	8,402	1,098.3	126.9	1,497.3	235,127.9	6,601.1	1,685,796.1	28.2	0.0	100.0
District	8,370	1,088.9	126.9	1,497.3	250,604.4	6,601.1	1,685,796.1	23.9	0.0	98.3
Parish	7,820	1,065.0	126.9	1,497.3	225,316.9	4,951.1	1,685,796.1	12.8	0.0	98.3
Random	8,400	892.9	126.9	1,481.4	158,651.3	3,613.7	1,214,901.9	6.9	0.0	95.9

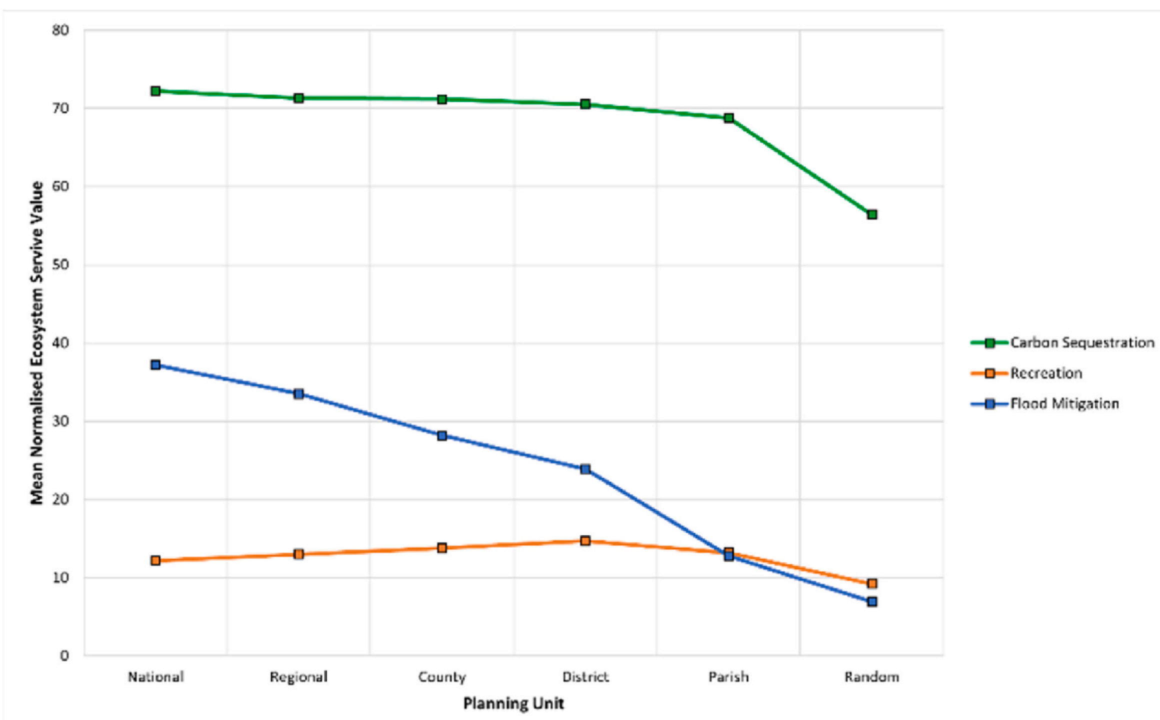

Fig. 7. Normalised mean ecosystem service provision from each of the modelled scenarios.

identifying areas able to support multiple ecosystem service objectives by calculating the average provision of the three services modelled, and selecting areas where this is highest. Alternatively, Pohjanmies et al. (2017) propose a 'land-sparing' approach, which optimises different areas of woodland for different purposes. For example, planting native woodlands near urban areas for recreation, and planting conifer plantations on less expensive land in more remote areas for carbon sequestration, rather than attempting to identify locations optimal for both. This approach would also fit some policy-driven funding opportunities for new tree planting that are designed to achieve specific environmental benefits, such as flood mitigation.

The modelling and spatial analysis used in this study are scale independent and therefore could be used in different contexts. Here, the methods are applied to a national-scale afforestation programme, with a spatial resolution of 1 km^2, and hotspots identified within planning units of varying sizes. With appropriate data however, the approach could be used at a range of scales and resolutions, from local to global. While the national scale results produced in this case study provide an indication of the most effective areas for afforestation, more detailed mapping could be carried out to optimise specific planting projects, such as those undertaken by large landowners or individual farms and estates, with afforestation by private landowners being the primary means of increasing forest area in the UK in recent years (Burke et al., 2021).

Table 4
The three largest contiguous woodland areas under each of the planning scenarios, compared with the largest existing woodland areas in England.

Woodland area (hectares)					
National	Regions	Counties	Districts	Parishes	Existing
654	570	284	127	12	465 (Kielder Forest)
613	379	217	125	11	208 (The New Forest)
554	256	158	100	9	137 (Thetford Forest)

5. Conclusion

Spatially targeting afforestation optimises the provision of multiple ecosystem services, but as congruence between the services modelled is low it is not possible to optimise them simultaneously. Results show that spatial targeting of woodland creation at the national scale has the potential to bring the greatest ecosystem service benefits, but risks overwhelming landscapes with new planting. Spatial targeting within smaller planning units results in more evenly distributed planting, but reductions in benefits compared with national-scale planning. Importantly, spatial targeting within even the smallest spatial units brings greater benefits than randomised planting, illustrating the benefits of considering multiple ecosystem services when planning woodland creation. These results do not imply a single 'correct' scale for planning, but instead illustrate how different ecosystem services benefits are affected by scale, and therefore the importance of considering appropriate spatial scales when seeking to optimise specific ecosystem service benefits from new tree planting. The methods we applied, to assess how a national afforestation programme could be spatially targeted to optimise multiple ecosystem services, are transferable and could be applied to other countries/regions, ecosystem services or planning units. This is important because different countries will have different priorities and requirements for their afforestation targets, and this method can be applied to highlight spatial trade-offs, synergies and to inform discussion between stakeholders.

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CRediT authorship contribution statement

Thomas Burke: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **Clare S. Rowland:** Conceptualization, Methodology, Writing – review & editing. **J. Duncan Whyatt:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Project administration, Supervision. **G. Alan Blackburn:** Conceptualization, Methodology, Writing – review & editing. **Jon Abbatt:** Conceptualization, Funding acquisition.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2023.103064.

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