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The Impact of Increasing Tree Cover on Landscape Metrics and Connectivity: A Cellular Automata Modelling Approach

Andrew Speak [1,*], Claire Holt [2], Polyanna Bispo [1], Ewan McHenry [3] and Matthew Dennis [1]

[1] Department of Geography, School of Environment, Education and Development, The University of Manchester, Oxford Road, Manchester M13 9PL, UK; polyanna.bispo@manchester.ac.uk (P.B.); matthew.dennis@manchester.ac.uk (M.D.)
[2] Institute of Science and Environment, Department of Forestry, The University of Cumbria, Carlisle CA1 2HH, UK; claire.holt@cumbria.ac.uk
[3] The Woodland Trust, Grantham NG31 6LL, UK; ewanmchenry@woodlandtrust.org.uk
* Correspondence: andyspeak33@gmail.com

Abstract

The United Kingdom has a low percentage cover of woodland, which exists in small, highly fragmented patches. Plans to increase the cover from 14.5% to 17.5% by 2050 will require guidance to help target the planting of new forests to maximise ecological connectivity. This study develops a novel approach to landscape simulation utilising real-world spatial boundary data. The Colne Valley river watershed is chosen as a study site. Three different future woodland creation goals (+10, 30, and 50%) are tested alongside manipulations of the mean new patch size and the mode in which new woodland is created in relation to existing woodland. Scenarios which expanded existing woodland and used riparian planting created larger, more connected patches with more core area. The model outputs are used to assess the impact of the UK woodland increase plans, and past woodland creation efforts are assessed. Increasing the percentage cover generally boosted connectivity, functional connectivity (species dispersals), and increased patch size and core area index. We suggest that proximal growth offers the greatest benefits in terms of biodiversity, but in terms of habitat connectivity smaller isolated woodland patches may also be needed as stepping stones to aid dispersal.

Keywords: SLOSS; riparian; fragmentation; afforestation; cellular automata model

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1. Introduction

Extensive native woodland habitat is very scarce in the United Kingdom, and the nation has one of the lowest percentage covers of woodland in Europe [1]. The remaining woodland patches are small in size, highly fragmented, and isolated within an agricultural and urban matrix [2]. There are plans, under the environment act of 2021 [3], to increase the percentage cover from 14.5% to 17.5% by 2050 with motivation coming from meeting net zero carbon goals [4], improving biodiversity [5], and promoting Natural Flood Management [6,7] amongst others. Since the 1940s, there have been improvements in the quality of UK woodlands with an increase in high forest of 46%, and the associated changes in ground flora, but ecological isolation persists [8].

The isolation of local ecological communities within a landscape—termed habitat fragmentation—can pose a considerable threat to biodiversity [9–11]. Species richness and abundance generally decrease at the patch level, with smaller patch areas [8,12], and animal movement between habitat patches is constrained, leading to higher local extinction probabilities [13]. The inherent complexity of ecological systems at the landscape scale has resulted in much debate about the impact of habitat patch configuration on biodiversity. Specifically, a focus has been placed on whether fewer larger or more numerous smaller (Single Large or Several Small: SLOSS [14]) patches will result in greater species richness for the same total habitat area [15]. Single large patches are capable of holding more species, as exemplified with birds [16], but species richness in numerous small habitat patches can also be large, if not greater, due to the fact that greater environmental variation (and, hence, more ecological niches) can be captured within their number [17] when looking at the landscape scale.

The impact of patch configuration and area on biodiversity has been the subject of much research [11,16]. Connectivity is the term used to describe the ability of species to disperse or migrate between or within habitat patches [18]. Fragmentation is, in a sense, the inverse of connectivity and has been described using many indices, including patch number, habitat edge length, core area, and patch shape complexity [19,20]. These landscape metrics are useful tools for quantifying habitat configurations and observing how they change through time, and their subsequent impacts on ecological communities [20]. However, the choice of metrics must be appropriate to the ecological processes of interest [21].

New woodland creation in the UK is constrained by issues of land availability with the majority of land available for conversion being agricultural, as this constitutes 70% of the UK land area [22]. Future planting of woodland will need to convert some of this land [23], and in the interests of food security concerns, this should be balanced against lost agricultural yields from that land. According to Bradfer-Lawrence et al. [4], 4.6 M ha of land are available for potential conversion to woodland (excluding certain land types such as high quality agricultural and peatlands), with greater long-term carbon sequestration possible from broadleaves managed for biodiversity rather than conifers managed for timber. Raising woodland cover to match countries like Finland, with its nearly 75% forest cover [1], is unfeasible, but creation of woodland networks in a targeted fashion to combat fragmentation without the need for monumental land conversion efforts is a viable option [24,25]. Using a simplified landscape model, a recent study illustrated how fragmentaion can have mixed impacts for conservation but is generally bad for restoration, and new habitat creation should be as near as possible to existing habitat to aid colonisation [26].

A desirable plan of action would include 'more, bigger, better, joined up treescapes' [27,28] with the right tree in the right place [29] and considering resilience to disease and climate change [8,28]. Connectivity of habitat networks can be increased by the targeted creation of linear woodland features such as hedgerows [30], transforming derelict transport infrastructure into 'greenway' networks [31], or boosting riparian planting. Riparian planting is frequently reported as a component of Natural Flood Management as UK policy makers are increasingly considering nature-based solutions for climate change mitigation and adaptation [6,32]. It has the further benefits of trapping sediment generated from agricultural practice [33] and shading river waters, consequently cooling them [34].

Building on the 'bigger, better' principles of Lawton et al. [27], Crick et al. [35] highlighted ways in which landscapes might better support biodiversity through the creation of nature networks that rely on enlarging and connecting high quality wildlife sites. These include corridors with a minimum width of 100 m, increasing tree cover to at least 20%, and using natural linear features such as rivers as existing connective features. Woodland creation activity sites next to existing woodland are prioritised [27] as this could increase the proportion of core habitat [36] in addition to aiding colonisation [26]. Investigations into whether woodland expansion by growing existing patches has advantages for habitat quality over more random approaches are called for. A recent study [37] simulated different habitat expansions and their effects on three connectivity metrics, finding significant increases in patch connectivity and species dispersal speed at just 10% increase. The generation of new habitat was entirely random and all non-habitat raster cells were available for conversion, which in reality is highly unlikely.

Modelling future woodland expansion scenarios is key to optimise planting approaches in the present. Manzoor et al. [38] used past land use changes and a Markov chain modelling approach to predict future tree cover in Wales under two scenarios. They found the current level of expansion is sufficient to meet policy goals; however, their scenarios were based on conservation factors and were not the specific spatial configurations of new woodland. Ecological processes are often studied using computer generated neutral landscape models [39]; however, constraints associated with land conversion into woodland in the UK require simulations to be based as much on the real world as possible. Synes et al. [40] used the species dispersal model RangeShifter to simulate different woodland creation scenarios in the UK with random or proximal growth being key components of the site and landscape scale conservation actions. They used a stochastic spatial algorithm and conservative scenarios of woodland creation (0.5%–4%), which are restricted in their resemblance to reality and with only superficial descriptions of how the scenarios were implemented in the software. There is a need for models that consider real-world landscapes and simulate woodland creation using realistic algorithms.

This study aims to demonstrate the benefits of real-world woodland creation scenarios, as there has been limited assessment of the evidence base for this beyond the more 'public goods' ecosystem services research on mostly coniferous plantations [41]. To this end, this study uses a simple cellular automata model [42] to simulate woodland expansion and linear riparian planting and demonstrates their impacts on landscape metrics. The main research question asks what impact different tree planting strategies, which consider the location of existing woodland, will have on landscape metrics. These metrics are crucial in understanding landscape dynamics, evaluating habitat restoration success, and communicating results. By including the less-studied riparian planting, it is hoped to uncover any effects of these linear features. The outputs will be examined through the lenses of SLOSS and functional connectivity to emphasise the link between woodland patch configuration and biodiversity. With these simulations, based as much as possible on real world geospatial constraints, and including a spatial analysis of current UK woodland characteristics, we will assess the efficacy of the environment act woodland creation goals.

2. Materials and Methods

2.1. Study Site

The Colne Valley river watershed was chosen for this study (Figure 1) as it contains a mix of landcover representative of UK landscapes, from uplands with grass, heather, and bracken dominating to lower altitude agricultural fields and woodland patches. The watershed also contains a significant urban land cover lower in the catchment, reaching the outskirts of the city of Huddersfield. An entire watershed was chosen in order to test targeted riparian woodland creation as a potential strategy and to compare this to creation elsewhere in the watershed. Riparian planting is projected for this area under National Trust plans, and the upland–lowland interface represents a prime location targeted for afforestation under current UK woodland creation schemes (NT personal communication; [43]). The location of the valley within the Pennines results in a cool, wet climate with rainfall higher than the national average (900–1300 mm). The altitude of the watershed ranges from 90 to 467 m.a.s.l.

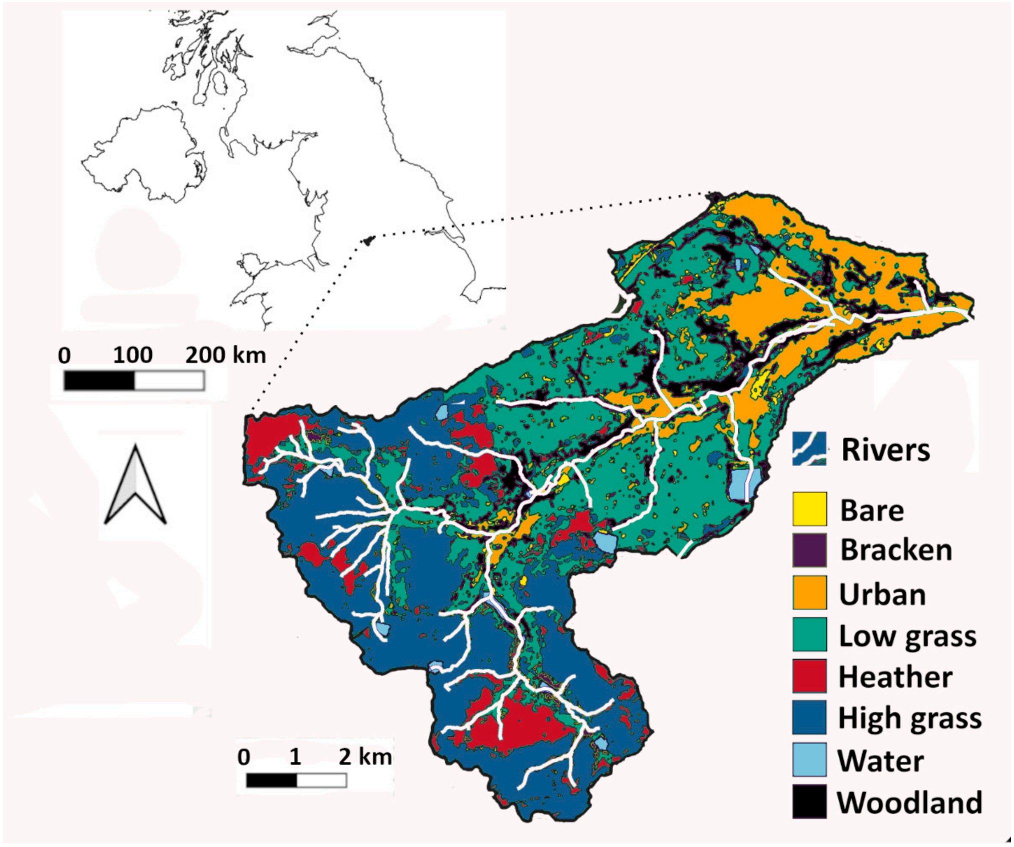

Figure 1. The location of the Colne Valley watershed with current landcover classes calculated in this study and the river network.

2.2. Landcover Maps

Existing landcover maps such as the CORINE land classification did not meet our spatial resolution criteria; therefore, we created a land classification for the watershed using recent 10 m resolution Sentinel-2 satellite images and a neural network classifier. Full details of the stepwise process, including R code for this and subsequent sections of the methodology, as summarised in Figure 2, can be found at https://github.com/andyspeak/landclass, accessed on 5 June 2025. Eight land classes were chosen—bare ground, bracken, upland grass, lowland grass, heather, urban, water, and woodland. Sentinel-2 image capture was taken on 25 June 2020, with less than 5% cloud cover and downloaded from Copernicus in a pre-processed form [44]. The pixel-based supervised classification takes a shapefile of polygons of known land types (ten samples per class) for training the model, which is then used to create prediction rasters. Three training models within the R caret package [45] (R v4.1.2) were used and compared for accuracy—Random Forest, Support Vector Machines, and Neural Network, with the best performer being selected for the final prediction raster output.

To elucidate the current situation of riparian woodlands more generally in the UK, we estimated their area using a buffer analysis (50 m) on Ordnance Survey (OS) open rivers data [46] and National Forestry Inventory woodland shapefiles for England, Scotland, and Wales [2]. Additionally, annual woodland inventory and creation data from 2013 to 2016 [2] were used to calculate the amount of woodland patches created adjacent to existing woodland or created as solitary patches over a 50 m distance from existing woodland, using buffer analysis and selection by location in QGIS (v3.16). The same 50 m river buffer was used in conjunction with CORINE land cover data from 2018 in vector format [47] to determine proportions of riparian land types in the UK.

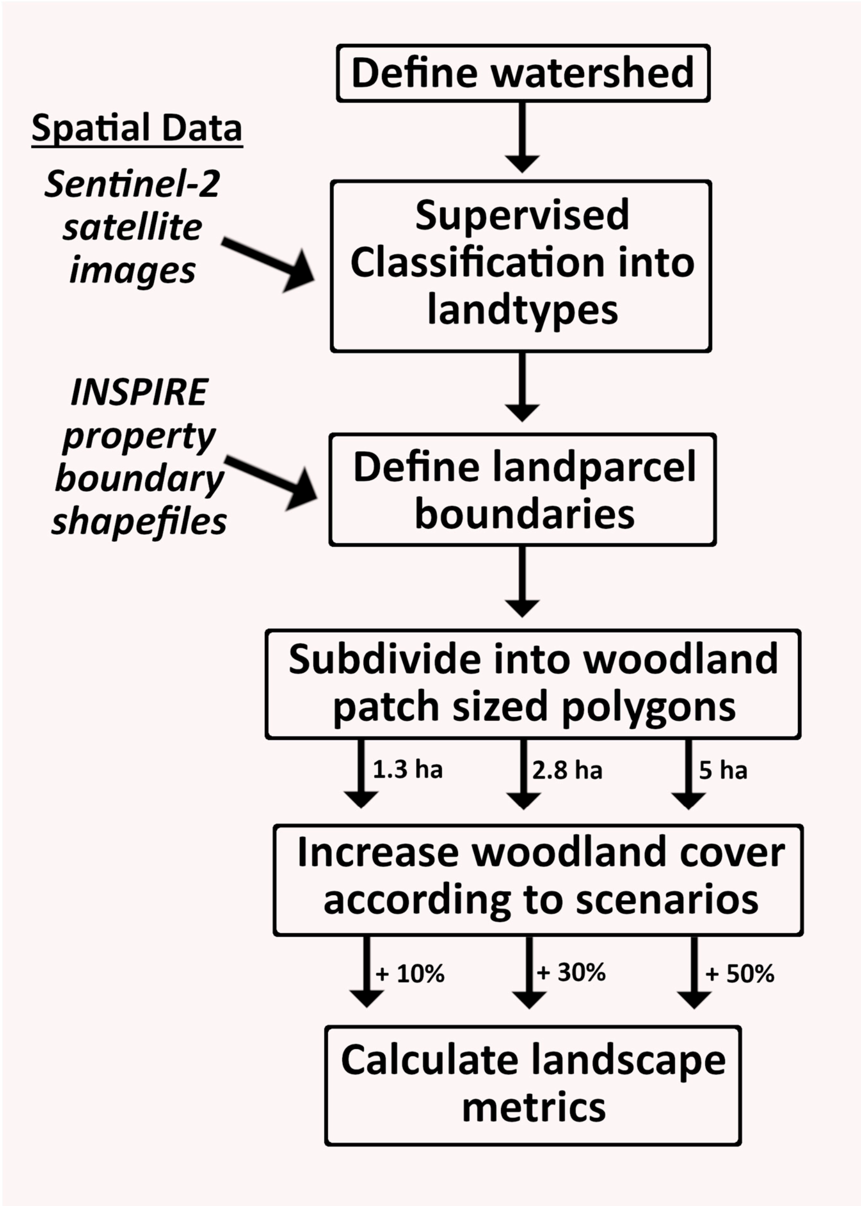

Figure 2. Workflow schematic for the simulation models.

2.3. Polygonisation

To model real-world woodland creation as much as possible, non-woodland areas were divided into patches based on property boundaries, and these patches were converted to woodland in their entirety, according to different scenario rules. Property boundary data were derived from the UK government INSPIRE dataset [48], which contains boundary polygons for freehold residential ownerships and subdivisions of rural land which often correspond with geographical borders such as agricultural field boundaries. This is suitable for the woodland creation scenarios as new woodland is often planted in spatial agglomerations based on existing boundaries, for instance converting a disused plot of agricultural land into woodland. Some polygons were very large, especially in upland environments. For these, a further step was taken to subdivide them into suitably sized polygons, or patches.

Subdivision of the landscape represented an opportunity to model the effect of patch area in woodland creation approaches. Three scenarios of mean average patch area were explored, denoted as PAT1.3 (1.3 ha), PAT2.8 (2.8 ha), and PAT5 (5 ha; Figure 3). PAT1.3

and PAT5 were determined as, respectively, the median and mean of existing National Forestry Inventory woodland patches [2]. PAT2.8 was taken as the mean field area within the existing subdivision of lowland fields, based on a random sample of 100 polygons visually identified as fields on Google Earth satellite images in QGIS (v3.16). The patch sizes, therefore, simulate woodland creation based on current woodland size or size of current land parcels potentially available for conversion.

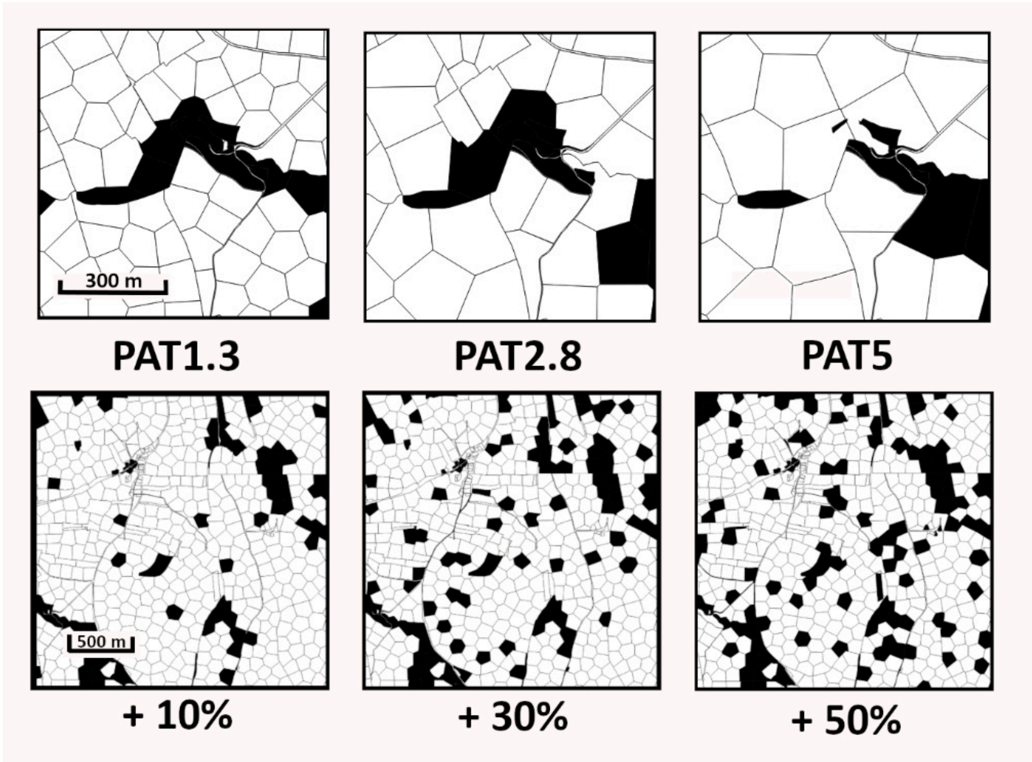

Figure 3. The three mean patch areas and three percentage woodland area increases (under the random growth pattern) modelled. Black polygons represent the "majority woodland" land type. Two different scales are used for visualisation purposes.

Polygons in the INSPIRE shapefile larger than their scenario's mean patch area were subdivided in turn, into Voronoi polygons that conformed to that scenarios mean patch area, using a bespoke R function which utilised k-means clustering (see github page). Each polygon was assigned a modal landclass from the underlying land classification raster.

2.4. Woodland Creation Scenarios

The vector shapefiles, subdivided and classified by land use for the three different mean patch area scenarios, serve as input for woodland creation simulation models, using a hypothetical model similar to Lee and Thompson [49]. Woodland coverage across the study area was increased by 10, 30, and 50% (relative to initial coverage), for each maximum patch area scenario (Figure 3), representing three scenarios of ambition for woodland expansion, and following four strategic targeting scenarios: random, proximal, riparian random, riparian proximal (Figure 4). Random, non-woodland polygons were converted to woodland at random; for proximal, polygons were iteratively converted to woodland at random from those that bordered existing woodland, causing woodland to grow by expansion. These two approaches are then repeated for riparian planting, with an additional constraint that converted polygons partially overlap a 50 m buffer around watercourses, which is an appropriate riparian delineation for agricultural lands [50], and meets the minimum width of 100 m suggested for nature corridors [35].

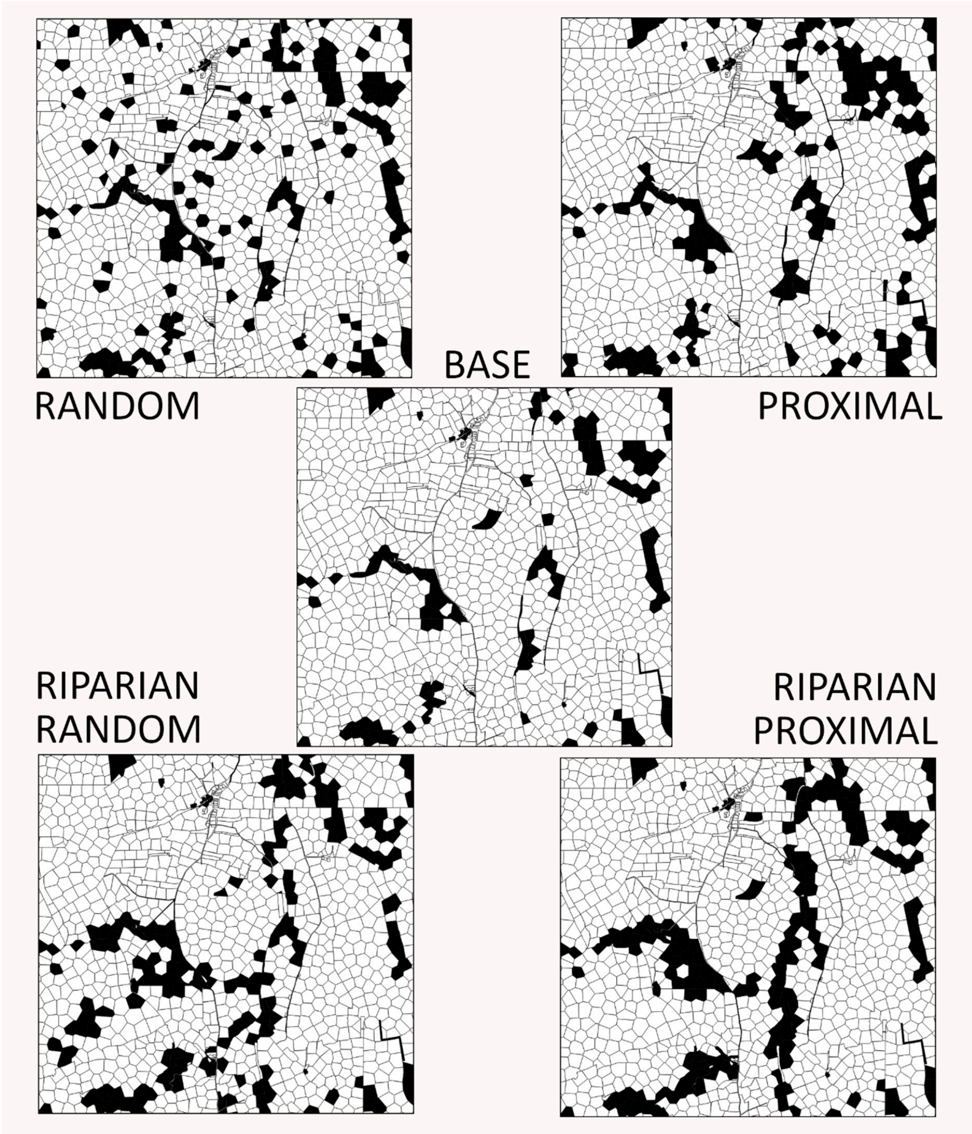

Figure 4. Four woodland creation strategic targeting scenarios (under the 30% ambition for woodland expansion scenario) and their relation to existing woodland coverage (centre).

Watercourses were defined using Ordnance Survey (OS) open rivers data [46]. While a fixed width buffer approach may only approximate variable riparian zones and their ecosystem services [51], it was appropriate for our simple model scenarios. For the smaller patch sizes of the PAT1.3 scenario, it was occasionally necessary to increase the buffer zone to 100 m to allow enough polygons for the +30% and +50% ambition scenarios to be reached. The woodland creation percentage increases encompass the UK reforestation target of 17.5% cover, which represents a rise in cover of 20.7% above present levels (14.5% at time of writing) and extend up to 50% to allow the elucidation of any trends, i.e., a continued increase or levelling off of benefits at such ambitious planting levels.

Non-woodland patches of bare ground, built/urban, and water were not available for conversion into woodland. Bare ground was predominantly bare rock and scree in upland environments. Patches above 300 m were also not available for conversion, as the upper limit for woodland creation in the UK is between 200 and 450 m. Finally, patches on land classed as high agricultural grade (top two grades out of five) were excluded [52]. Each scenario was run 100 times, and the output vectors were rasterised back to the original 10 m resolution of the land classification raster in readiness for calculation of landscape metrics.

We assume, for the purposes of landscape connectivity metrics, that pre-existing and newly created woodlands are equally able to support woodland biota and facilitate species dispersal, representing a future state of woodland after approximately 20 years.

These scenarios, by generating patches of different quantities and sizes in a highly realistic landscape simulation, allow the investigation of the SLOSS debate. Different combinations of patch size and quantity can be tested in terms of their effects on landscape metrics and consequently provide the basis for postulations about their effect on wildlife ecology.

2.5. Landscape Metric Calculation

Landscape metrics were calculated at the landscape level for the woodland patches using the "landscapemetrics" package [53]. The metrics chosen were aggregation index, mean patch area, core area index, edge density, Euclidean nearest neighbour, largest patch index, number of patches, and perimeter area fractal complexity. These were chosen for their simplicity and interpretability [54]. Edge depth was 10 m corresponding to one pixel in the raster files. Where statistical comparisons were necessary, these were calculated using pairwise Kruskal–Wallis, across the different combinations of percentage woodland increase, average patch size, and growth scenarios, and tabulated in the Supplementary Materials.

In order to calculate habitat functional connectivity, we used a recently published Edge-weighted Habitat Index [55], which utilises a logistic function to link matrix patch area to distance decay effect of the habitat edge using habitat costs and edge effect data from Eycott et al. [56]. This was backed up by the calculation of least cost pathways from an origin in the centre of the landscape to 15 points around the edges of the landscape, using the same edge effect data for calculating the resistance layer. The analyses were carried out using the "leastcostpath" package [57], and improvements to species movements were calculated as the percentage decrease in the accumulated cost of the least cost path in the scenarios as compared to the baseline situation.

The aforementioned UK reforestation target rise in cover of 20.7% above present levels can be assessed in terms of its effect on the landscape metrics. This was derived from running the model 100 times. The middle mean patch size of PAT2.8 was used and non-riparian scenarios (allowing a comparison of random versus proximal growth) considered for simplicity.

3. Results

3.1. Baseline Data

The accuracy of the training models for the land classification map (Figure 1) was very high with an accuracy of 98.9% and a kappa statistic of 0.98 for the best model which was the Neural Network.

The buffer analysis of National Forest Inventory woodland maps revealed that 17% of the 622,381 UK woodland polygons had rivers running through them, which accounts for 40.9% of the woodland area. 9.9% of UK woodland area was within 50 m of the OS river network, with a comparable percentage for the Colne Valley (10.7%). The analysis of new woodland patches between 2013 and 2016 revealed that on average, 47% of new woodland patches were created adjacent to existing woodland and 19% were created as solitary patches over 50 m distant from existing woodland. The main CORINE land types within 50 m of UK streams and river are woodland (29%), peatland (21%), moorland (14%), grassland (13%), urban (13%) and the remaining 10% agriculture, parks, and bare.

3.2. Landscape Metrics

The calculated metrics are displayed, grouped by relevance to SLOSS (Figure 5) and connectivity and shape (Figure 6). Increasing the ambition for woodland expansion from

10% to 50% increased mean patch area, core area index, largest patch index, edge density and aggregation index across all strategic targeting scenarios. Mean patch area in particular, almost doubled with 50% woodland cover increase. The number of patches only rose above the baseline levels within the random, whole landscape scenarios, otherwise they fell below baseline. Increasing percentage cover also decreased mean nearest neighbour distance.

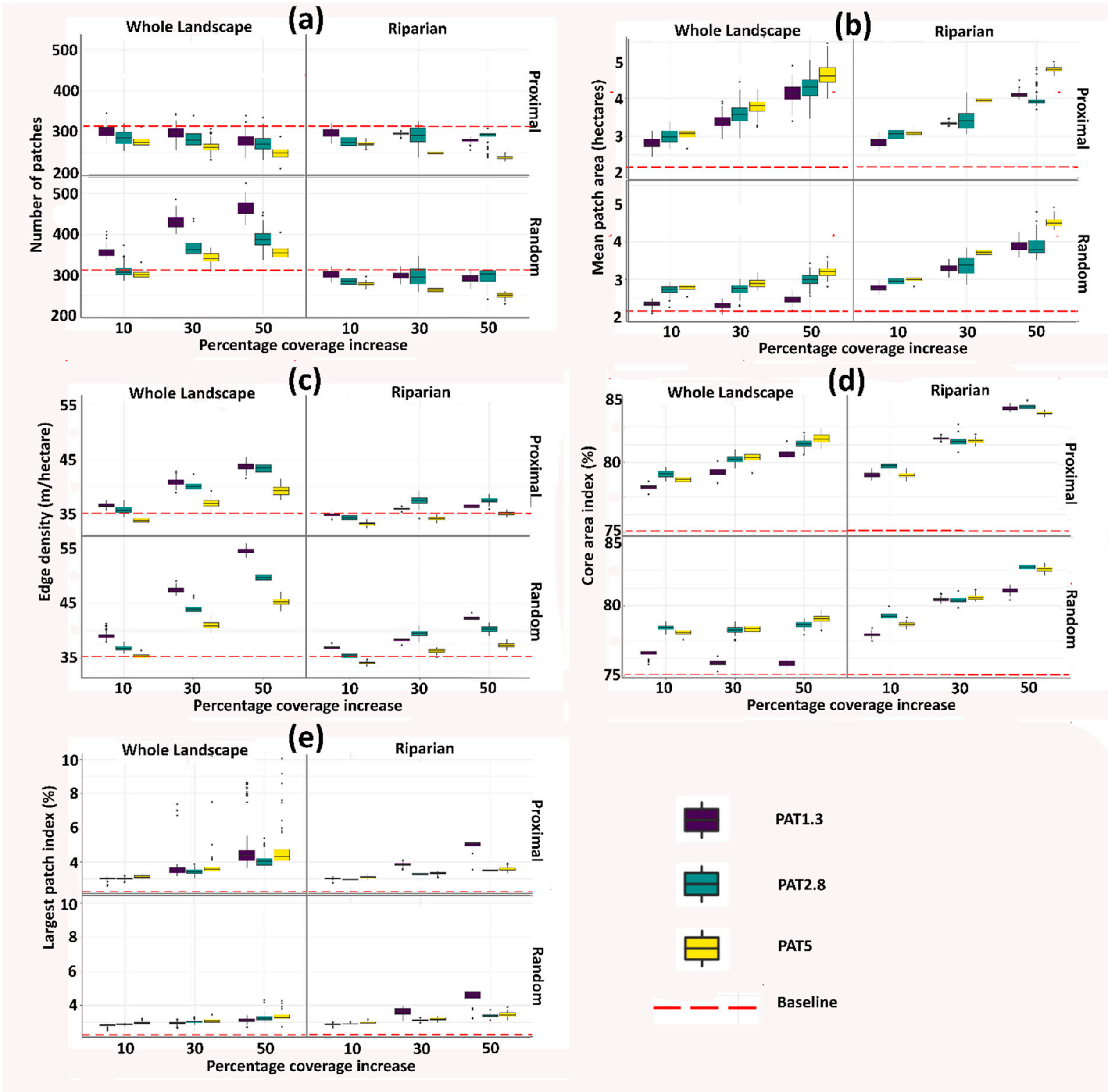

Figure 5. Landscape metrics related to patch size for the different modelled scenarios at different levels of woodland coverage increase; (**a**) Number of patches, (**b**) Mean patch area, (**c**) Edge density, (**d**) Core area index, (**e**) Largest patch index. For each metric, landscapes were simulated N = 100 times. Red line is the baseline.

Increasing maximum new patch area in the simulations (PAT1.3 to PAT5) had the general effect, within each expansion ambition group, of decreasing the number of patches and the edge density in all strategic scenarios and increasing the core area index in the non-riparian scenarios. Smaller new patch areas also resulted in small decreases to average patch area, distance to neighbour and aggregation index, which are all associated with spreading habitat conversion on patches more evenly across the landscape. New patch area had very little effect on the largest patch index except for in the riparian scenarios above 30% where the index increased, which was the scenario associated with close-to-all available habitat in the riparian area being converted to woodland.

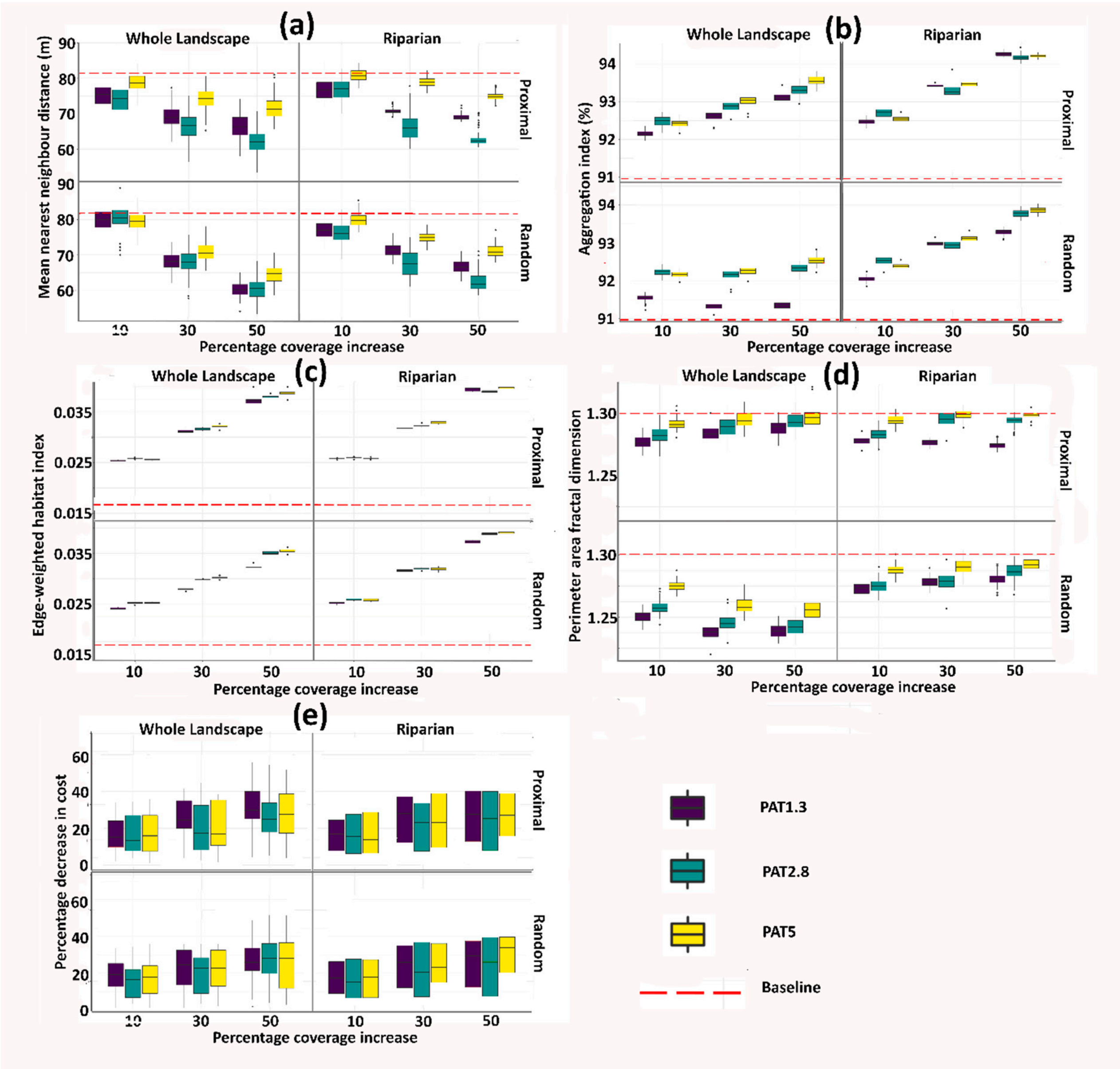

Figure 6. Landscape metrics related to connectivity and shape for the different modelled scenarios at different levels of woodland coverage increase; (**a**) Mean nearest neighbour distance, (**b**) Aggregation index, (**c**) Edge-weighted habitat index, (**d**) Perimeter-area fractal dimension, (**e**) Percentage decrease in accumulated cost along least-cost pathway. For each metric, landscapes were simulated N = 100 times except for the habitat index with N = 5 and least cost with N = 15. Red line is the baseline.

The edge-weighted habitat index increased with each percentage cover increase, reaching a 130% increase with a 50% increased cover (for PAT2.8, proximal general scenario). Increasing mean new patch area had a negligible effect on the index, apart from in the random, whole landscape scenario where the increase is significant (Kruskal–Wallis; 10%, H = 9.38, $p < 0.01$; 30%, H = 10.52, $p < 0.01$; 50%, H = 9.80, $p < 0.01$). Pairwise comparisons between riparian/general and proximal/random combinations shows that while significant (Supplementary Materials) the actual differences are small, with the largest differences in mean values between the random general scenarios and the others, showing that proximal and riparian are very similar in their effects on habitat connectivity.

The fractal dimension shape index in Figure 6 shows that increasing the percentage cover has minimal effect on the shape complexity (even though the differences are significant, Supplementary Materials), however increasing patch area tends to raise the complexity of the patches, as the edges become more jagged, akin to decreasing the resolution of digital images. With regards the planting strategies, the fractal index is lower, indicating less shape complexity, in the random, non-riparian scenario.

The least cost pathways show an average decrease in cumulative cost between 15 and 30% with no significant differences between scenarios except for a slight increase in conductance with rising percentage cover; however, only one combination was significant (PAT1.3, proximal, whole landscape: H = 6.56, p = 0.04).

The national UK woodland expansion target produces a diverse range of predicted responses in the landscape metrics calculated here, with the largest increases being in patch area and largest patch index. Smaller increases were also suggested in aggregation and edge density, while decreases were suggested in core area index, fractal dimension and distance to neighbour. Patch number was suggested to increase slightly in the random scenario and decrease when existing riparian woodland was expanded. The UK target increase in cover was predicted to increase the edge-weighted habitat index by 72.9% in the proximal general scenario, and 66.3% in the random (for PAT2.8; Table 1).

Table 1. The percentage change from baseline values in each index at the national UK woodland expansion target of 20.7%, and percentage decrease in accumulated cost along least-cost pathway, assuming a mean new patch size of 2.8 ha in the whole landscape.

Metric	Scenario	% Change at 20.7%	S.D.
Aggregation	Proximal	+2.4	0.1
	Random	+1.8	0.1
Mean patch area	Proximal	+50.4	7.8
	Random	+27.8	5.0
Core area index	Proximal	+6.7	0.5
	Random	+3.9	0.4
Edge density	Proximal	+8.0	1.9
	Random	+16.5	1.2
Nearest neighbour	Proximal	−15.0	5.2
	Random	−9.2	4.6
Largest patch index	Proximal	+49.1	4.8
	Random	+36.7	1.9
Patch number	Proximal	−10.4	8.1
	Random	+14.7	5.1
Edge-weighted habitat index	Proximal	+70.2	0.1
	Random	+64.3	0.1
Perimeter area fractal	Proximal	−1.5	0.7
	Random	−4.4	0.5
Cost decrease	Proximal	−18.2	10.1
	Random	−17.9	9.6

4. Discussion

This work has developed a novel approach to simulating the UK landscape, basing the digitisation as much on real world phenomena and constraints as possible. This has allowed some interesting land use change models to be developed to test future woodland expansion approaches. The simulations of different ambitions for woodland expansion, strategic targeting and mean new patch area scenarios have revealed several different responses of the landscape metrics, here divided by two main themes.

4.1. SLOSS

The simple physical consequences of increasing woodland cover are bigger patches, with more core area. This nudges the landscape towards one dominated by fewer, larger patches with the concomitant benefits of allowing for natural succession and stability and reducing edge interactions with a hostile matrix [58]. Focussing on riparian planting increases this move towards one joined up 'super-patch'. The largest patch index increased in the riparian scenarios above 30% with smaller patches because in these scenarios, nearly all the land available within the riparian buffer zone was converted into woodland. However, it must be noted that the changes in metrics in terms of real values were not that high. For instance, core area index increases were only on the order of a few percent (and none greater than 10%) and the largest patch index only increased by a couple of percent, even in the 50% increase scenarios. Average patch area however doubles in the 50% scenarios

In order to move the landscape to one dominated by several small patches, with a higher density of edge habitat, a completely random, whole landscape planting approach is suggested. Similarly, with regards the size of new patches, decreasing new woodland patch area meant that more patches were needed to achieve the same area of woodland expansion, thus increasing the number of patches and edge habitat. Quine and Watts [54], in their simulations, found this could lead to increased fragmentation by increasing the number of small, isolated patches. Patch size should definitely be considered if there are goals of core versus edge habitat to be considered.

4.2. Connectivity and Shape

Increasing the woodland cover directly increases connectivity as the patches become more aggregated and closer together (Figure 6a,b), and new patches can connect previously separated woodlands. The edge-weighted habitat index shows clear increases with increasing percentage cover, as the patches become bigger, closer and more interconnected. The random woodland creation scenarios generally had the lower indices and riparian and proximal were very similar (although statistically different) indicating the benefits, albeit small, of tending towards single large patches over several small (and well-spaced). Further development of metrics such as the edge-weighted habitat index may prove useful in elucidating the effects of patch size and location on biodiversity, because they consider dispersal distances, edge surface and cost values of matrix landcover types within their calculation. Species range expansion was enhanced by adjacent woodland growth in the Synes et al. study [40], however this depended strongly on landscape configuration and effects were negligble below levels of change of 2%.

With regards average patch size, smaller patches lowered the aggregation of woodland in the landscape, even with proximal growth scenarios, as smaller patches are less likely to bridge gaps between existing patches. Further to this, decreases in the mean least cost path cumulative cost were not significantly affected by increases in percentage cover, although a general upward trend was observed. The values of 15%–30% decrease in cost were comparable to the 5%–35% increases in species movement speed at a 10% increase in woodland in three UK regions [37]. The other scenario elements did not affect the least cost paths, indicating that, in terms of species dispersal, only increasing the proportion of woodland might be expected to aid species dispersal and there is no need to consider targeted planting.

Larger patches increased the fractal shape complexity, which could be due to the utilisation of Voronoi polygons as new patches and the impact of different scales on the shape and angularity of these polygons (see Figure 3). The polygons mostly had between 4 and 7 sides, so of relatively shape, but their interaction with borders in the cadastral data could produce some erratic shapes. Riparian woodlands will have their own fractal shape characteristics, in addition to lower edge density and higher aggregation, as they are elongated along river networks. The rivers themselves possess fractal complexity, being highly branched. Increasing percentage cover had a small positive effect on shape complexity apart from in the random whole landscape scenario where the addition of many singular, isolated polygons caused a decrease in overall complexity.

Woodland shape in terms of biodiversity is only important via its effect on edge and core proportions and subsequent species considerations. For instance, bird species capable of occupying smaller woodlands were more prevalent in the lobes of complex larger woodlands [59]. However, studies that show a correlation between woodland shape complexity and biodiversity usually obtain this result as a result of studying woodlands where a higher influence from human management (and thus lower biodiversity than natural woodlands) has created the woodlands with a more uniform and compact shape [60].

Overall, average new patch area did not influence the landscape metrics to such an extent that warrants recommendations to be made about the size of future woodland plantations. For instance, the only situation where smaller patches would be recommended would be if a large number of patches is desired with consequent increases in edge habitat.

4.3. UK Woodland Expansion Target

The UK national target for woodland expansion (20.7% above current levels) produced some substantial changes in the metrics, relative to their current state. These included 50% larger mean patch area, 7% higher core area index, 15% less distance to the nearest neighbour, 18% reduction in the least cost pathway cost, and 70% increase in the realised habitat index. These predictions were for the proximal growth scenario, with the random scenarios producing smaller changes. We tentatively suggest that targeted expansion of existing woodland patches would most benefit ecological connectivity, relative to more random habitat creation. This is supported by empirical evidence suggesting that new woodland created adjacent to existing established woodland grows faster, taller and with more structural diversity [61]. A random approach to woodland creation in a modelling study in the Chilterns was found to be less effective than spatially targeted planting in terms of fragmentation as measured by landscape indices [49].

It is, therefore, reassuring that past woodland creation efforts, as revealed in this study, have tended towards proximal growth with nearly half of new patches created next to existing woodland and only one in five new patches created as solitary islands. Based on the responses of landscape metrics observed in this research, we recommend a continued mixed approach to new woodland creation but with a tendency towards proximal growth as this resulted in the greatest changes in the landscape metrics associated with biodiversity. This mixed approach to habitat creation has been termed single large and several small (SLASS [58]) and ensures large enough habitat patches for a greater number of species to thrive but also provides important stepping stones for species dispersal.

Riparian planting did not differ substantially from the proximal planting approach and the two in combination did not amplify each other's effects, except for with lower edge density and higher aggregation than the other scenarios. Both approaches have the same structural outputs, with fewer but larger patches dominating. The main difference being that riparian woodlands are more linear in shape as they follow the rivers. It must also be noted that the limited space available for riparian planting creates an artefact in our scenario design which leads to the creation of one large, aggregated patch.

Riparian land in the UK is already dominated by woodland (29% in the 50 m buffer zone) and nearly 10% of all the woodland is within this zone. Targeted planting in this zone could certainly increase connectivity and create larger woodland patches, and this would complement plans to reintroduce the beaver to the UK [62] by creating extensive habitat. In fact, the increased connectivity would benefit a whole range of species and rivers represent a fairly stable habitat that is unlikely to change (excepting major floods or river diversion). Riparian planting is also potentially less controversial when (public consultations are involved. The next dominant landtypes, peat and moors, may not be suitable for tree planting, however, leaving only an estimated 18% (agricultural and grassland) for conversion. The 'England Woodland Creation Offer' is a Forestry Commission initiative [63] which offers landowners up to £10,200 per hectare of new woodland created, with the upper range of the grant scale for riparian planting.

4.4. Considerations

The use of landscape metrics is not without its issues such as sensitivity to data resolution, scale and study area extent [64]; however, we avoid these by examining one landtype within the same landscape and at a high resolution. There is also debate as to the degree which these metrics meaningfully measure differences in the potential for landscape scale biodiversity [65], as the collapsing of land cover information into classes can complicate the development of ecologically meaningful interpretations [66]. The use of the realised habitat index adds value to the study by its more nuanced approach to modelling edge and matrix effects [55].

The use of models to simulate natural processes always comes with limitations and these include oversimplifying the woodland creation process into fixed patches and growth patterns. In reality, it would be a complex, spatially variable interplay of planting approaches and constraints such as climate change and urban expansion. New woodland would have different ecological properties to old woodland which would affect its role in connectivity. The study only considers patches of woodland for the landscape metrics and does not include potentially significant landscape connection features such as solitary trees and hedgerows, which can assist dispersal in some species and have local positive population effects [30]. Future studies could improve on these models by adding this extra level of detail.

Reforestation is a complex issue encompassing diversity in sites, species, forest types and cultural and economic constraints [67]. Any woodland creation schemes need to follow extensive guidelines of land preparation, ecosystem service desires, soil properties, water table, etc. [5]. Thankfully there are recommendations in place such as using adaptive management, allowing for natural regeneration wherever possible, involving stakeholders and protecting existing forest first [22,67]. Targeted planting, to achieve biodiversity goals, will require the cooperation of landowners. Farmers, in particular, respond to multiple factors in deciding whether to convert farmland into woodland [23,68], and there is some resistance at present, with farmers' media failing to promote the benefits of farmland conversion [69]. Economic incentives, like the aforementioned England Woodland Creation Offer are in place which have been shown to have positive associations with biodiversity indices [70]. Considerable policy intervention will be necessary to overcome barriers such as establishment costs, loss of annual income and the cultural division between farming and forestry [71]. When monetising carbon sequestration, forestry can be a more economical land use than pasture [23], which should be disseminated alongside the results of studies, such as the present one, which demonstrate the benefits of new woodland for addressing ecological fragmentation.

An analysis of past woodland creation efforts and riparian land use revealed that proximal growth has been preferred in the UK and riparian woodland is very common, perhaps because rivers and their floodplains were less likely to be exploited for agricultural development. There is still room for increasing the riparian woodlands and this can act as a means of enhancing connectivity for biodiversity in addition to their role as Natural Flood Management.

Nature recovery is an overarching objective of woodland creation [5] and the UK woodland cover increase goal of 20.7%, when assessed in terms of our models, produced some considerable changes in the landscape metrics. Namely, larger mean patch area and more core area, plus patches that are closer together and more connected in terms of an edge-weighted habitat index. We suggest that proximal growth confers the greatest benefits in terms of biodiversity, but smaller isolated woodland patches may also be needed as stepping stones to aid dispersal.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16071081/s1, Kruskal–Wallis significance tabulation.

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Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. The code used to generate scenarios and land classifications is available on the github page mentioned in the methods. Shapefiles of the three land division patch sizes and a raster of the land classifications for the study area are available at: Reviewer link: http://datadryad.org/share/xUz7YbOc2KvJ5-blhYEGdmo1fKqLRaNJdbOtnnSzp3c, accessed on 5 June 2025.

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Abbreviations

The following abbreviations are used in this manuscript:

OS	Ordnance Survey
SLOSS	Single Large or Several Small
SLASS	Single Large and Several Small

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