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RESEARCH ARTICLE

New woodlands created adjacent to existing woodlands grow faster, taller and have higher structural diversity than isolated counterparts

Samuel Hughes[1,2], William Kunin[1], Kevin Watts[3,4], Guy Ziv[5]

Creating native woodland is a policy goal globally, and one strategy to maximize woodland creation benefits in limited space is to target efforts to extend existing woodlands. There is evidence to support spatially targeting habitat creation for biodiversity, however, there is little evidence of how this affects a habitat's structural development. Here, a space-for-time study using light detection and ranging (LiDAR) data assesses how the structure of recently created woodlands, are affected by the presence of an adjacent older woodland. Recently created native woodlands were identified across the Isle of Wight UK using historical maps and satellite imagery. Canopy height and foliage height diversity were derived for all woodlands from LiDAR data collected at two different time points (2011 and 2021), and linear models were used to test for any differences in these structural metrics between sites with an adjacent older woodland, and those without. The percentage change in woodland height between the two time points was also tested. In woodlands created adjacent to older woodlands, canopy height was found to be higher by an average of nearly 2 m, and foliage height diversity was found to be on average 4.7% higher, using the 2021 data. Growth rates between 2011 and 2021 were not significantly different between the groups, although young adjacent woodlands grew the most on average. This research shows that creating woodlands adjacent to existing older woodlands reduces the time taken to create tall and to a lesser extent structurally diverse habitat, which may lead to early biodiversity benefits.

Key words: canopy height, forest restoration, forest structure, LiDAR, structural diversity, woodland creation

Implications for Practice

- Woodlands created adjacent to existing woodland grow faster, taller and have higher structural diversity than their isolated counterparts.
- This has the potential to speed up the benefits delivered by woodland creation and reduce the time-lag between conservation action and biodiversity response.
- However, these initial biodiversity benefits may be reduced as isolated woodlands reach similar levels of growth and structural diversity.
- We demonstrate the use of LiDAR to examine the growth, structural and potential value of woodland creation for biodiversity.

Introduction

Across the world, attempts are being made to reverse centuries of deforestation by creating and restoring native woodland (Keenan et al. 2015; Davies 2017; European Commission 2021). The reasons for this afforestation are multifaceted, including carbon sequestration to combat climate change (Bastin et al. 2019; Holl & Brancalion 2020), restoring and protecting biodiversity, and providing cultural/recreational benefits (Di Sacco et al. 2021). More recently, it has been argued that planting trees should not be considered a panacea, and that treating it as such can lead to unintended negative results, such as the destruction of other important habitats or the displacement of productive farmland (Holl & Brancalion 2020). However, ambitious targets remain, for example the UK government has pledged to plant 30,000 ha of trees a year by 2025 (HM Treasury 2020), the European Union plans to plant 3 billion trees by 2030 (European Commission 2020), and Canada has embarked on a 2 billion trees commitment (Government of Canada 2020). Evidence is needed to inform decisions regarding where to spatially target woodland creation and restoration in ways which maximize benefits in limited space.

Tree planting decisions are often influenced by a need to decrease fragmentation and increase ecological connectivity

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[1] School of Biology, University of Leeds, Leeds LS2 9JT, U.K.
[2] Address correspondence to S. Hughes, email bs17smh@leeds.ac.uk
[3] Forest Research, Alice Holt Lodge, Farnham GU10 4LH, U.K.
[4] Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, U.K.
[5] School of Geography, University of Leeds, Leeds LS2 9JT, U.K.

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among native woodlands (Peterken 2000; Humphrey 2003; Melles et al. 2011). This is exemplified by Haddad et al. (2015) who demonstrated that globally, forests are small and fragmented with 70% of them being within 1 km of a forest edge. One strategy which has been shown to successfully combat this is to extend existing mature woodlands (Quine & Watts 2009). There is evidence showing that targeting woodland creation this way benefits biodiversity by increasing the colonization rate for a range of woodland specialist species (Opdam et al. 1984; Dunning et al. 1995; Brunet et al. 2021). Synes et al. (2020) have also used individual-based models and simple land cover change scenarios to show that targeting habitat creation adjacent to existing habitat is potentially one of the most effective strategies to conserve biodiversity in a changing climate. However, many such studies assume that the recently created habitat is instantly suitable for species to colonize and fail to account for the considerable temporal lag in structural development (Jackson & Sax 2010; Lira et al. 2019; Watts et al. 2020).

There are many reasons why it is important to consider structural metrics when planning woodland creation, not least for ecosystem services such as carbon storage and timber production (Vashum & Jayakumar 2012; Felipe-Lucia et al. 2018; Lutz et al. 2018). Woodland structure is also known to have strong effects on biodiversity (Smith et al. 2007): woodlands that reach canopy closure sooner are likely to provide refuge for woodland specialist species more quickly (Harmer et al. 2001; Brunet et al. 2011), and woodlands with greater structural diversity have been shown to increase species richness (MacArthur & MacArthur 1961; Dracup et al. 2015; Fuller et al. 2018).

Monitoring woodland height and structure across large spatial extents can be achieved using light detection and ranging (LiDAR), a technology that allows for the recording of three-dimensional forest structure. Recently, LiDAR has been used specifically in restoration ecology across the globe: in Brazil, drone-borne LiDAR was used to compare two different planting densities and two different management types in restored forests (Almeida et al. 2019*a*), other studies in the region have shown it to be accurate at estimating many metrics pertinent to restoration success, such as aboveground biomass and tree species diversity (Almeida et al. 2019*b*), work in Mexico has used LiDAR to create high resolution reference models for forests on different landform types (Wiggins et al. 2019), and a study in Oregon used LiDAR to assess fuel accumulation in restored forests to combat wildfires (Olszewski & Bailey 2022).

The present study uses discrete return LiDAR data from two points in time (winter 2011 and winter 2021) to look at how canopy height and foliage height diversity (FHD) of recently created woodlands is affected by the presence of adjacent, older woodland neighbors, which were mature and well established at the time of the recent woodland's creation. Although light availability can be a limiting factor in plant growth (Shirley 1929), we expect that LiDAR data will show trees planted adjacent to an existing woodland have increased growth in height, because older trees compete for light causing planted saplings to grow taller and avoid shade (Craine & Dybzinski 2013). Older adjacent neighbors may also buffer the target woodlands from wind effects reducing mechanical stress, and plants are known to increase growth when mechanical stress is reduced (Liu et al. 2007). We predict that older adjacent woodlands will also lead to an increase in FHD (a metric of structural diversity), by providing additional propagules resulting in more rapid understory development.

Methods

Study Area and Sample Design

The Isle of Wight was chosen as an ideal study region for two reasons: (1) there have been recent efforts to create new native woodlands adjacent to mature often ancient woodlands (existing since 1,600), thereby reducing fragmentation (Quine & Watts 2009); and (2) there are no populations of deer or gray squirrels on the island which means there are no complex interactions between woodland growth and grazing pressure (Spake et al. 2020). As deer fencing is now funded as an option within the current woodland creation grant in England (Rural Payments Agency 2021), this means woodlands created on the Isle of Wight will be representative of future woodlands created across the rest of the country. The Island has a maritime climate with an average summer temperature between 13°C and 20°C, an average winter temperature between 3°C and 9°C and average precipitation of around 870 mm (Met Office 2020). The climate is consistent across the island and thus elevation (increasing up to 240 m above sea level) is expected to control for any variation in temperature.

The UK National LiDAR Programme provided data for the year 2021 (Environment Agency 2022), where data from 2011 were downloaded from Defra (Department of Environment Food & Rural Affairs 2011). Year 2011 was chosen as this was the previous year with the most coverage over the island and a gap of 10 years should leave enough time for growth rate observations (Fuentes-Montemayor et al. 2022). Both products are aircraft-based LiDAR data collected by the UK Environment Agency during winter, they were both tested against ground control samples to ensure that the absolute height error is less than ±15 cm. The mean point cloud densities were 1.17 and 1.56 per m^2 for 2011 and 2021, respectively, and both products are discrete return LiDAR with 4 returns per pulse. Using two different sets of LiDAR data has risks as they may result from different collection and postprocessing protocols. However, these were both collected in winter by the same agency and were both tested for errors against ground surveys, thus we will cautiously use them to compare which woodlands grew more than others but will not use them to infer absolute growth rates.

Sample woodlands ($n = 63$) were selected from the National Forest Inventory (NFI) 2015 (Forestry Comission 2015), after removing all ancient and non-broadleaved woodlands, and then filtering out all plots larger than 1 ha or which were not covered by the LiDAR data (Fig. 1). We focused on small plots as these are more likely to be affected by an adjacent woodland. Woodland ages were identified using historical Ordnance Survey maps (EDINA 2020), and historical satellite imagery, accessed on Google Earth Pro version 7.3 (Google Inc 2020). Woodlands planted in 2005 or later were not included, as not enough time has passed between their creation and the available LiDAR data.

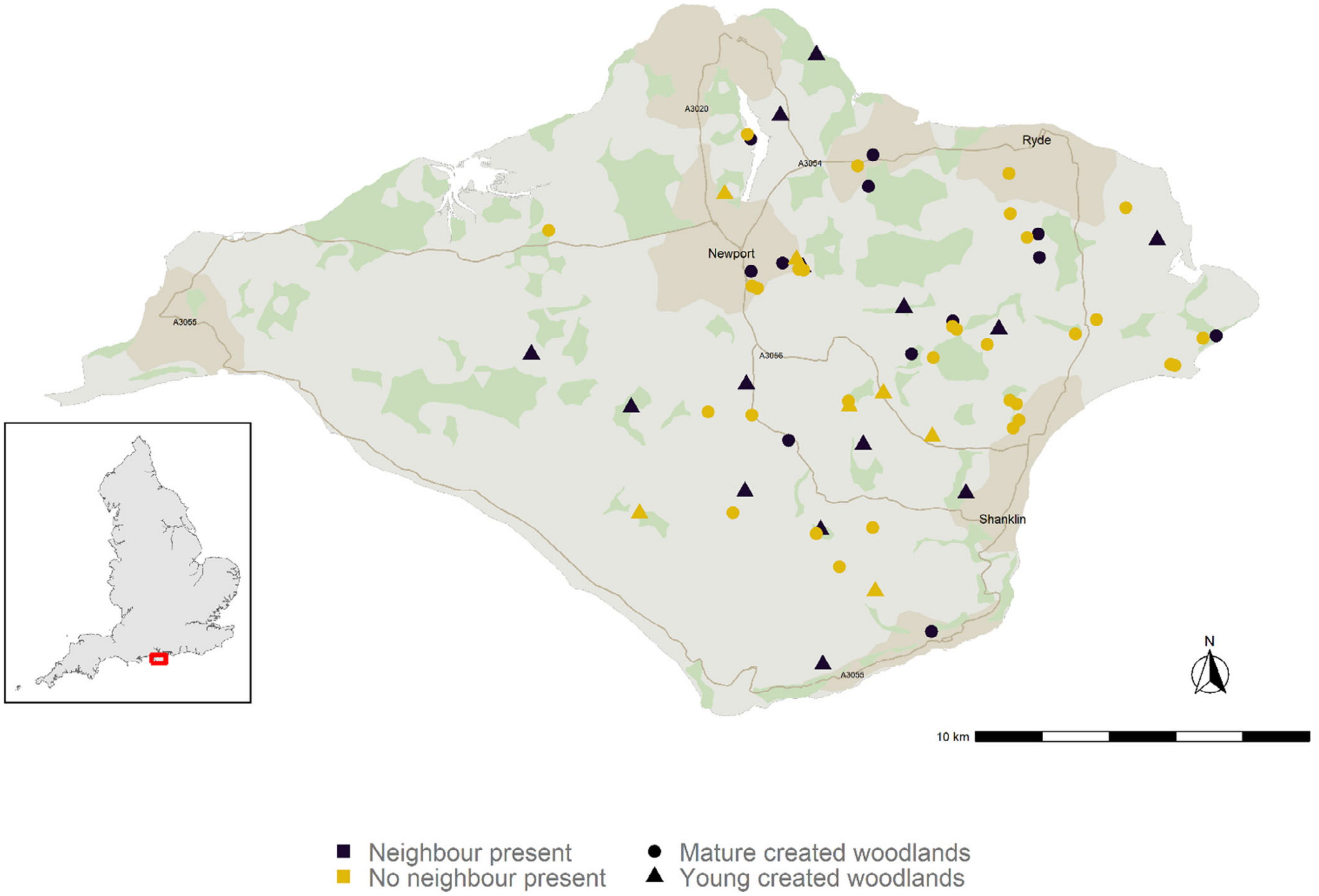

Figure 1. A map showing the study region within the Isle of Wight. Mature created woodlands were created between the years 1970 and 1990, where young created woodlands were created between the years 1995 and 2005. The presence of an adjacent mature neighbor is denoted by color. All woodland plots used in the study were below 1 ha in area. Background vectors and labels provided by Ordnance Survey (https://www.ordnancesurvey.co.uk/business-government/products/open-zoomstack) under the Open Government License (http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/).

Woodland creation dates ranged between 1970 and 2000 although few woodlands were found originating in the 1980s, and so these were pooled with woodlands created in the 1970s. From now on, woodlands created between 1970 and 1989 will be referred to as "mature created woodlands", and woodlands created between 1995 and 2005 will be referred to as "young created woodlands" (Fig. 1). There were no woodlands originating in our sample between 1989 and 1995.

The historical records were also used to determine whether woodlands were adjacent to or isolated from an existing older woodland at their creation. Adjacent woodlands were defined as closed canopy woodlands (at least 20 years old) which boarder the adjacent created woodland, but we also considered lines of mature trees to be adjacent older woodlands if they ran parallel and not perpendicular to the adjacent created woodland (Fig. 2). All but two adjacent created woodlands shared at least a quarter of their edge with an adjacent older woodland. The lowest percentage edge in common between adjacent woodlands was 10%. Geological information was also extracted to each woodland using the "DiGMapGB-50 Rock Unit" product (EDINA 2008). Created woodlands were 0.65 ha on average, and their spread across age groups, adjacency and geology is displayed in Table S1.

Tree species information is not included in the NFI dataset, meaning that any differences in height between woodlands could be caused by the specific species occupying each woodland. To eliminate this possibility, we visited a subset of publicly accessible woodlands from our sample (13 adjacent 17 isolated). On these visits the two most dominant tree species were visually identified by the recorder to see if tree species were evenly spread between adjacent and isolated created woodlands. Most sites were dominated by *Fraxinus excelsior* and *Quercus robur*, with 12 isolated and 13 adjacent woodlands including one or both in their two most dominant species. Other less common species include *Acer campestre*, *Crataegus monogyna*, and *Corylus avellana*. One woodland was dominated by *Alder glutinosa* where one other had been invaded by *Salix* species. The vast majority of this subset represent typical native broadleaved woodlands which are encouraged in a UK context, and therefore we are confident that the species mix is not confounding results.

LiDAR Processing

LiDAR point clouds were processed using R version 4.0.3 (R Core Team 2020), using the packages *LidR* (Roussel

Figure 2. Two examples of recently created woodland connected to adjacent older neighboring woodlands. On the left the recently created woodland is connected to a closed canopy woodland, where on the right the recently created woodland is connected to a strip of mature trees. These more linear strips of trees were considered as adjacent neighboring woodlands as long as they ran parallel to the created woodland as in the picture.

et al. 2020), and *Raster* (Hijmans & Etten 2012). All the following steps were completed for both the 2021 and 2011 LiDAR data.

Point clouds were first checked for noise using the "noise_ivf" function from the LiDR package, which showed there to be very little noise in the data overall. The point-clouds for each woodland had their ground returns classified using a progressive morphological filter (Zhang et al. 2003), and a digital terrain model (DTM) was then produced at a 1 m grain size using a triangulated irregular network. Visually inspecting cross-sections of our point clouds showed very few omission or commission errors, and any commission errors tended to occur below 1 m in height and points this low were excluded from the analysis anyway, this was consistent between young and mature created woodlands. The classified point-clouds were normalized by computing the difference between points and the DTM so that every point represents the height relative to the ground.

From these point clouds canopy height was extracted as the relative height at the 90th percentile (RH90) of returns and FHD was extracted using the entropy function from the *LidR package*. This function modifies Shannon's evenness index (DeJong 1975) by assuming that maximum diversity would include evenly distributed foliage in all 1 m height bins below the max canopy height, whereas Shannon's evenness index would normalize the corresponding diversity index using only the height bins occupied by foliage. The proportion of LiDAR returns in each height bin, for each woodland can be viewed in Fig. S1. It is possible to set a uniform maximum canopy height for all woodlands to normalize Shannon's diversity index (van Ewijk et al. 2011). However, for this study the maximum height of each respective woodland was used instead, as setting a uniform maximum height would penalize shorter woodlands simply for being short. Height is an important component of FHD, but it is measured already by the RH90 metric.

Other factors which could potentially affect woodland height and thus confound results were also obtained. Topographic metrics including elevation, slope and aspect were computed from the DTMs using the "Terrain" function from the *Raster* package. Aspect was then converted to a "Northness" variable which ranged between -1 (due south) and 1 (due north) and calculated by taking the cosine of the aspect radians. Each derived metric was extracted to the relevant woodland using area summarizing statistics. Canopy height was extracted as RH90, FHD was extracted as the index calculated by the entropy function whereas elevation, slope, and Northness were extracted as averages.

Statistical Analysis

Three linear models assuming Gaussian errors were used to analyze the data. The first model tested whether being planted next to an adjacent older neighbor had a significant effect on the height of a created woodland, using the RH90 variable from the 2021 data only. The second model tested for significant effects of an adjacent neighbor on structural diversity using FHD, again this only looked at the most recent 2021 data. The final model tested for the effects of adjacency on the percentage change in RH90 between 2011 and 2021, by dividing the difference in RH90 between the 2 years by the RH90 in 2021 and multiplying this by 100.

All models included variables of adjacency, woodland age categorized as young or mature woodlands, underlying geology, mean elevation, and aspect (Northness), the significance of each variable was tested using a *t*-test. Slope was not included in any model as it is strongly correlated with elevation and replacing elevation with slope did not improve or greatly worsen model fits. Residual plots were checked to ensure they fit a Gaussian distribution and variance inflation factors were checked to ensure no multicollinearity was affecting results.

Results

The presence of an adjacent mature neighbor significantly increased the RH90 of the created woodlands in 2021 (Fig. 3) by an average of 1.99 m ($p < 0.05$, $t = 2.3$, $df = 55$, $R^2 = 0.47$) (Table S2) and increased the FHD (Fig. 4), by an average of 4.7% ($p < 0.05$, $t = 3.2$, $df = 55$, $R^2 = 0.4$) (Table S2). Examples of these differences can be viewed in Figure 5 which are the plotted point clouds of one adjacent created woodland and one isolated created woodland. The percentage change in height between 2011 and 2021 was not significantly affected by adjacency, however, Figure 6 shows that woodlands with the greatest average increase in height were young woodlands adjacent to older neighbors. It is important to note that this change in height should not be considered as an accurate absolute change but must only be considered to see if certain woodlands grew more or less than others, as the two sets of LiDAR data may have small differences in sampling protocols.

Individual height profiles for each woodland are shown in Figure S1. These plots show the proportion of LiDAR returns in each height bin of a woodland, from which the overall FHD is calculated. These show that any difference in height or FHD between created woodlands is not because some simply fail to establish. They are also useful to visualize how height profiles have changed between the 2011 and 2021 data.

Unsurprisingly woodland age significantly affected both its height (Fig. 3) and its FHD (Fig. 4), on average young created woodlands were 5 m shorter ($p < 0.01$, $t = -5.32$, $df = 55$, $R^2 = 0.47$) (Table S2) and had an 11% lower FHD value ($p < 0.01$, $t = -5.55$, $df = 55$, $R^2 = 0.4$) (Table S2) than mature created woodlands. The underlying geology did not significantly affect either height or height diversity. Elevation did negatively affect woodland height ($p =\leq 0.05$, $t = -2.13$, $df = 55$, $R^2 = 0.47$) and FHD ($p < 0.01$, $t = -2.06$, $df = 55$, $R^2 = 0.4$) (Table S2) although the effect sizes were small with a 2 cm decrease in height and a less than 0.001 decrease in FHD for each metre increase in elevation. Other topographic variables did not significantly affect woodland height or FHD (Table S2).

Discussion

The present study adds to the evidence base informing where to plant and restore native woodlands, not by focusing on biodiversity directly, but by evaluating structural metrics which have the potential to enhance it. The results show that woodlands planted adjacent to older woodland neighbors grow taller and to a lesser extent become more structurally diverse than their isolated counterparts. This effect was smaller in mature created woodlands than it was in younger created woodlands, and when looking at the percentage change in height between 2011 and 2021, young created woodlands planted adjacent to older neighboring

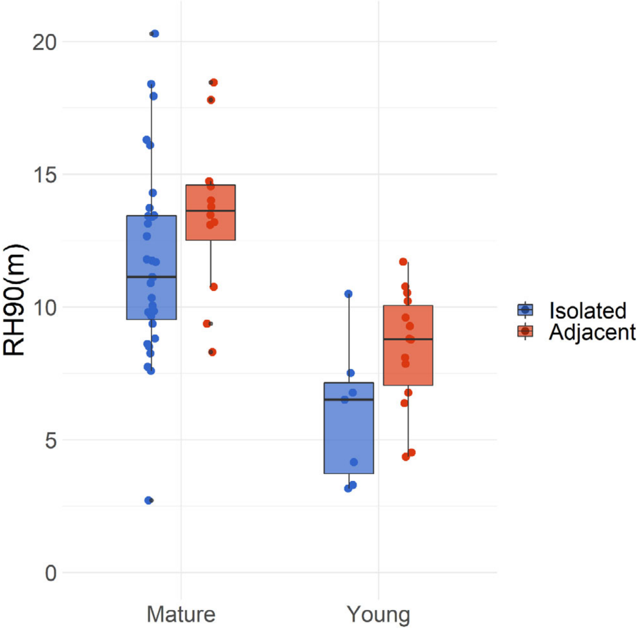

Figure 3. A boxplot showing how the 90th percentile of canopy height (m) is affected by woodland age ($p < 0.01$, $t = -5.55$, $df = 55$) and adjacency to mature neighboring woodlands ($p < 0.05$, $t = 2.3$, $df = 55$). This index was measured from woodlands in the Isle of Wight using discrete return LiDAR data collected in the winter of 2021.

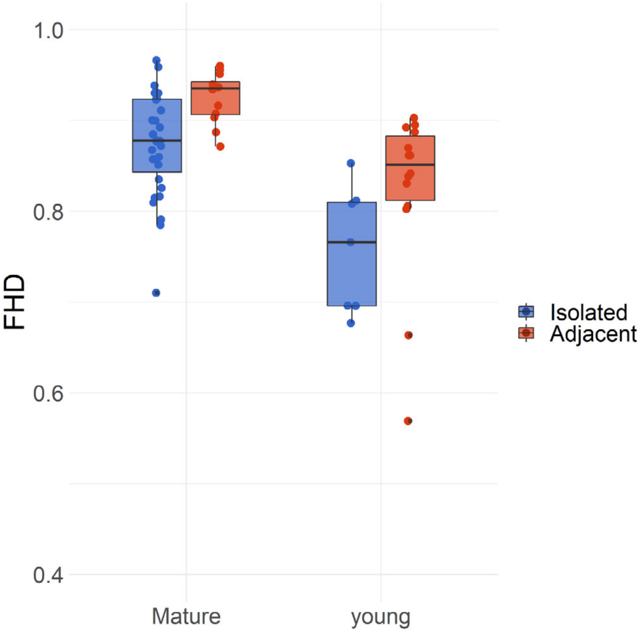

Figure 4. A boxplot showing how foliage height diversity is affected by woodland age ($p < 0.01$, $t = -5.32$, $df = 55$) and adjacency to older neighboring woodlands ($p < 0.05$, $t = 3.2$, $df = 55$). This index was measured from woodlands in the Isle of Wight using discrete return LiDAR data collected in the winter of 2021 and calculated using a modified version of Shannon's evenness.

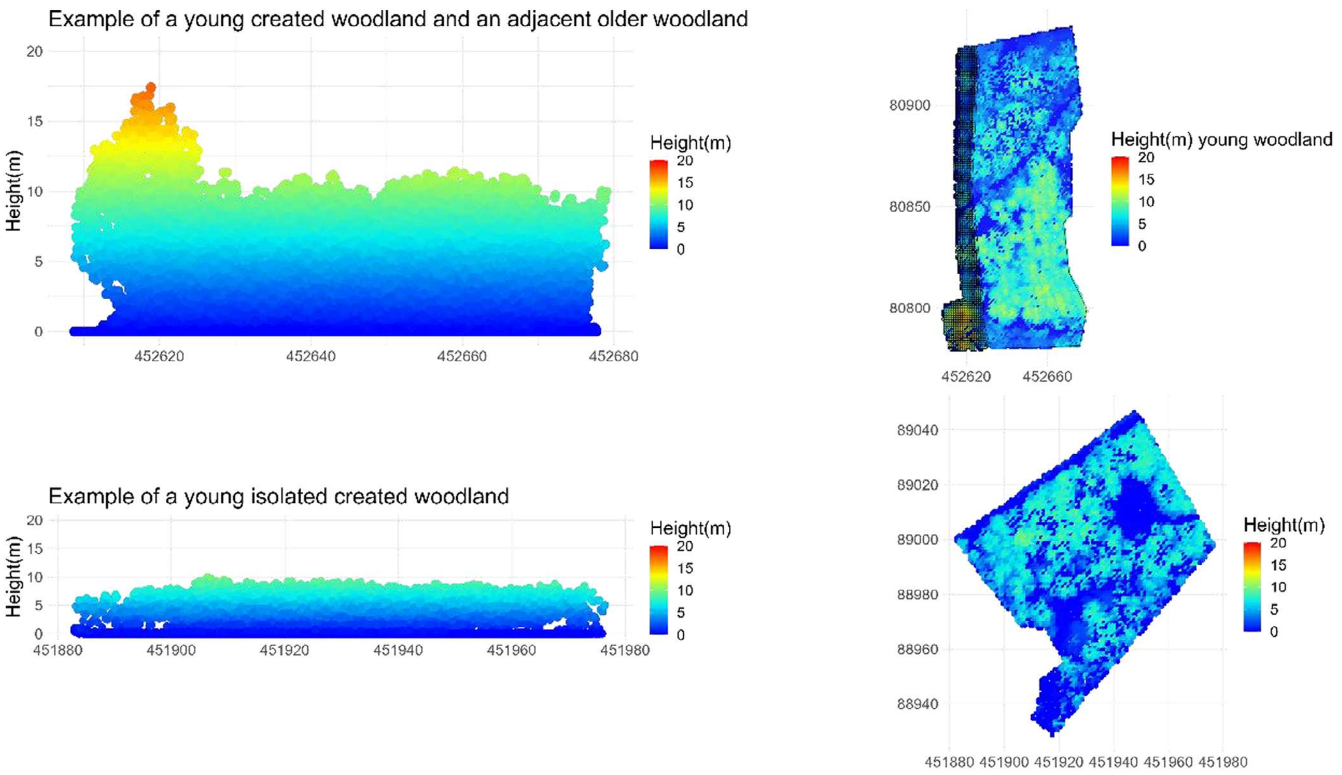

Figure 5. Examples of two young created woodlands, one (on the top row) planted adjacent to an older strip of woodland, and the other (on the bottom row) planted in isolation. The left column shows a cross-section of each woodland, for the young woodland planted adjacent to an older woodland, this older woodland is included in the cross-section. The right column is a bird's eye view of each woodland, the adjacent older neighbor for the top woodland is colored darker. Both created woodlands are roughly the same age. This helps visualize how the woodland created adjacent to an older neighbor has grown taller.

stands grew more on average than their older or isolated counterparts, although not significantly. This suggests that the difference in height and structural diversity may begin to even out with age. Other studies have found trees at higher elevations to be shorter (Uzoh & Oliver 2006; Messaoud & Chen 2011), we also found this here, although the effect sizes were very small possibly due to the low range in elevation across the study area (0–240 m).

There are a few possible mechanistic explanations for the significant increase in height caused by adjacent older neighbors, the first involving light competition, which provides a reason for trees to grow tall despite maintenance trade-offs (Iwasa et al. 1985). Taller neighbors would cast shade on saplings encouraging them to grow taller and reach sunlight. A second explanation for this phenomenon is to do with wind buffering and the removal of edge effects. A study from Meng et al. (2006) experimented with tethering trees to see how this affected their growth; the authors found that tethered trees had lower bending moments allowing them to expend less energy anchoring themselves and more energy growing taller. This relates to the present study, as an established adjacent neighbor would act as a wind buffer for recent woodlands. A study with greater statistical power could attempt to further detect this effect by including a parameter of aspect relative to neighbor, here it would be expected that woodlands buffered in the direction of prevailing winds would grow taller than those buffered from different directions. By including the direction of shade cast from a mature woodland the effects of wind and light competition could also be disentangled.

The effect of an adjacent older woodland on the FHD of target woodlands was much smaller than the effect on height, however there was still a significant difference. Woodland height itself is known to be a key determinant of FHD (Aber 1979), which would explain the increased FHD in woodlands growing adjacent to older neighbors. This is because as woodlands get taller there is simply a larger range of possible foliage heights (Müller et al. 2018). However, this study normalized FHD by maximum tree height within each site to measure FHD per se. As woodlands reach older successional stages their vertical complexity increases due to canopy closure and natural rejuvenation in the understory (van Ewijk et al. 2011), if the presence of an adjacent woodland increases tree growth to match that of an older woodland then it may cause vertical complexity to increase quicker. Mature neighbors may also be acting as seed sources (Pereira et al. 2013) promoting an increased density of foliage below the canopy in the form of saplings, potentially well before newly planted trees are mature enough to reproduce. A more likely explanation is that trees nearer the adjacent neighbor grow taller, but this affect reduces with distance across the site, making for a more varied canopy height.

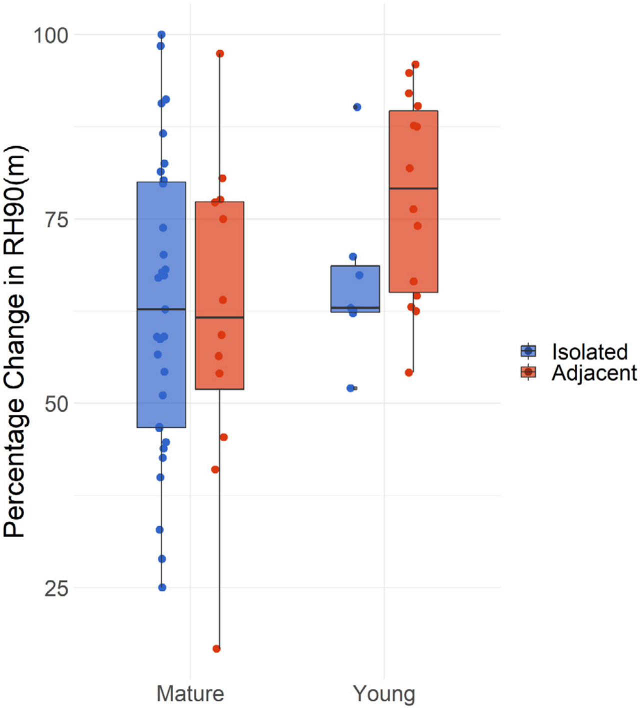

Figure 6. A boxplot showing the effects of woodland age and adjacency to a mature woodland neighbor on the percentage growth between 2011 and 2021. Adjacency did not significantly affect growth rates, however on average young woodlands with adjacent neighbors grow more than their isolated counterparts. As LiDAR data collected in 2011 will had a different sampling protocol to that collected in 2021 it is important not to take this percentage change as raw growth, but instead consider it relative to other woodlands.

This study took place in temperate Western Europe, and the nature of small target woodlands created adjacent to remnant patches of older woodland is very typical of this region. However, the question of how to enhance structure in restored woodland is important globally (Stanturf et al. 2014), especially as we enter the UN Decade on Ecosystem Restoration (UNEP and FAO 2022). In the tropics, for example there are many restoration techniques being tested to not only improve biodiversity outcomes but to quickly create structurally diverse woodland. Natural colonization, applied nucleation, and direct seeding have all been proposed as ways to obtain a more natural stand structure (Freitas et al. 2019; Holl & Brancalion 2020). The present results may be able to further enhance these techniques, especially as they require nearby seed sources for success, which would be provided by adjacent older neighboring woodlands.

An important point to note about these results is that the Isle of Wight lacks any wild deer population. Deer are known to reduce the sapling density and height of regenerated or planted forests (Gill & Beardall 2001). It would be easy to assume that the presence of deer would lead to uniformly shorter woodlands, however recent work has shown this may not be the case. Spake et al. (2020) have found that forest cover in the surrounding landscape can increase the likelihood of deer damage, though this is also dependant on climate and matrix composition. If this is the case, then then we could expect the results to be modulated by the presence of deer. An interesting future study could compare recent woodlands on the Isle of Wight with those in mainland Britain situated in similar conditions. This could also test between fenced and nonfenced plots in landscapes where deer are present, considering that future woodland creation schemes will have deer control (Forestry Comission 2020). Another factor which could be important to these findings is that of woodland patch size, we controlled for this by focusing on smaller woodlands, so we did not need to account for it in statistical models. Larger woodlands with a lower percentage of their edge boarder an adjacent older neighbor may not be as strongly affected by this neighbor as the smaller woodlands in our study. Future work could address this.

The policy and management implications of these findings will pertain to the targeting of woodland creation and the potential benefits for biodiversity and ecosystem services. There is much evidence showing that ecological connectivity increases colonization rates (Opdam et al. 1984; Peterken & Game 1984; Petit et al. 2004), and recent research has shown that habitat creation should target the extension of existing habitat (Synes et al. 2020). However, it has also been argued that woodland restored in small fragments will also be beneficial to biodiversity by creating greater landscape heterogeneity and providing stepping-stones between existing fragments (Hodgson et al. 2012; Arroyo-Rodríguez et al. 2020). The present study adds a new dynamic to this decision-making process by showing that woodland habitat reaches structural maturity quicker, with potentially greater biodiversity benefits, when planted adjacent to older woodland neighbors. Depending on management objectives this may present a more palatable strategy than creating fragmented patches of woodland.

We are in a time where conservation actions increasingly need to be targeted in the most cost-effective way (Rappaport et al. 2015; Synes et al. 2020), and the results of this study present an often unconsidered factor in restoration planning which could benefit biodiversity.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Height profiles of each individual created woodland calculated as the proportion of LiDAR returns in each 1 m height bin.

Table S1. Displaying how woodland samples are spread across ages, adjacent or isolated and geology.

Table S2. The results of 3 linear models assuming Gaussian error structures: the first predicting canopy height in the form of Relative Height at the 90th percentile, the second predicting the foliage height diversity, and the third predicting change in canopy height between 2011 and 2021.

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